

Tracing human mobility and cultural diversity  
after the fall of the Western Roman Empire:  
A multi-isotopic investigation of early medieval  
cemeteries in the Upper Rhine Valley

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*... was kann da nicht alles vorgekommen sein in einer alten Familie. Vom Rhein – noch dazu.  
Vom Rhein. Von der großen Völkermühle. Von der Kelter Europas!*

Carl Zuckmayer, Des Teufels General



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## I. INTRODUCTION

### *Introduction to the topic*

The 5<sup>th</sup> and 6<sup>th</sup> centuries AD<sup>1</sup> were times of complex and drastic transformations in the political, social and cultural landscapes of Europe. As a consequence of the decentralisation of the Roman administration, geographic mobility across Europe increased. Non-Roman groups invaded the Western Roman Empire, either forcefully by conquering territories or as allies that were settled in order to provide military assistance. These dynamic processes in combination with other developments finally contributed to the gradual dissolution of the Western Roman Empire by “Romano-barbarian kingdoms” struggling over sovereignty in the late 5<sup>th</sup> century. One of the most successful of these groupings were the Franks. Starting as a group of undistinguished barbarians north and east of the Rhine frontier in the 3<sup>rd</sup> century, it was a Frankish king of the Merovingian dynasty who governed the former Roman provinces in northern Gaul by the end of the 5<sup>th</sup> century and finally dominated a territory from east of the Rhine to southern France in the 6<sup>th</sup> century (James 1988; Nonn 2010; Becher 2011; Ewig 2012).

The written sources do not inform us about the extent to which these overall socio-political transformations had affected local communities in the northeastern frontier provinces. The archaeological remains indicate profound changes during the 5<sup>th</sup> and 6<sup>th</sup> centuries. One of these was the creation of a new burial practice. In many regions of Western and Central Europe, people started to bury their dead in new burial grounds, so-called “row-grave cemeteries” (*Reihengräberfelder*), in west-east oriented inhumation graves with especially rich grave goods (Halsall 1995, 7–11; Ament 2003, 362–365; Fehr 2008, 76–96). Traditional archaeological approaches based on historical narratives attribute the rich burials to the immigration of “Germanic” groups in the form of a settlement wave or a continual infiltration process. Single grave goods, combinations of grave goods and other elements of the funeral rite were used to prove the immigration of foreign groups and individuals (e.g. Koch 1998; Siegmund 2000; Bierbrauer 2004). Newer approaches criticise a sheer “migrational” explanation for the interpretation of material remains. The emergence of the “row-

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<sup>1</sup> All dates refer to AD unless otherwise stated.

grave horizon” is rather interpreted as a cultural reorientation of the local communities in response to the social and political dynamics of the time. The huge number of graveyards and graves, as well as the rich and diverse grave goods, indicate that not only the elite but also the broader masses, whether of “Roman” or “Germanic” origin, viewed the creation of a new funeral rite as a tool to stabilise the social order and to demonstrate prestige and social conditions (Brather 2004; Brather 2007, 124; Halsall 2007, 104; Fehr 2008; Fehr 2010, 725–784).

However, based on the archaeological record alone it is not possible to pursue this discussion. The application of radiogenic strontium isotopes of human tooth enamel is an established tool for the identification of first generation immigrants. The method is based on the variation of  $^{87}\text{Sr}/^{86}\text{Sr}$  values which depend on bedrock age and composition. The isotopic fingerprint of a region is transmitted from bedrock to soil, water, plants and animals and finally into the human body. By comparing the local biologically available strontium signature of a region with the strontium signature of human dental enamel, it can be determined if a person obtained food and drink from this area during tooth formation, thereby aiding the identification of migrants (Ericson 1985; Price et al. 2002a; Knipper 2004; Bentley 2006; Montgomery 2010). The analysis of stable oxygen and carbon isotopes from structural carbonate of tooth enamel is also increasingly used to answer questions regarding human mobility and provenance (e.g. Schroeder et al. 2009; Laffoon et al. 2013). As the use of only a single isotope system is limited by the problem of equifinality, oxygen and carbon can provide independent evidence concerning individual provenance as they vary according to different principles. Oxygen isotopes in tooth enamel vary according to geographical location and climatological factors (Longinelli 1984; Luz et al. 1984; Luz/Kolodny 1985; Bowen/Wilkinson 2002), while carbon isotopes vary between marine and terrestrial resources as well as between plants using different photosynthetic pathways (Krueger/Sullivan 1984; Lee-Thorp et al. 1989; Ambrose/Norr 1993).

Recent isotopic studies of early medieval cemeteries in Central Europe have mainly focused on migration events which are described in the written sources, such as the Anglo-Saxon migration to England (Budd et al. 2003; Budd et al. 2004; Millard et al. 2005; Montgomery et al. 2005; Brettell et al. 2012a; Hughes et al. 2014) or the migration of the Langobards from the Lower Elbe region to Italy (Tütken et al. 2008a,

21–24; Maurer et al. 2012; Knipper et al. 2012a). In addition, several early medieval cemeteries in Bavaria were investigated to examine the evidence for, and patterns of, mobility (Schweissing/Grupe 2000; Schweissing/Grupe 2003b; Hakenbeck et al. 2010). No investigations have yet been conducted in regions located in the borderland of the former Roman Empire in the Rhine area. For these regions no large migration events were reported in written sources but, based on the location along the Rhine, an important trading route and contact zone between different cultural areas, extensive cultural exchange and the presence of migrant individuals could be expected.

#### *Purpose of the study*

This study focuses on the isotopic investigation of human individuals from graves of the late 5<sup>th</sup> and the 6<sup>th</sup> century from three early medieval cemeteries situated on the western bank of the northern Upper Rhine Valley. This is a region where the processes of the 5<sup>th</sup> and 6<sup>th</sup> centuries are particularly well exemplified. Based on written sources, it is assumed that the Burgundians occupied the region in the first half of the 5<sup>th</sup> century, followed by an immigration of Alemanns and Frankish groups in the second half of the 5<sup>th</sup> century and during the 6<sup>th</sup> century (Knöchlein 2003, 135–139). However, archaeological research has shown that Roman structures continue to exist until the second half of the 5<sup>th</sup> century when *villae rusticae* and Roman graveyards were finally abandoned and new early medieval settlements and burial grounds were established (Bernhard 1997; Bernhard 2007; Bernhard 2008a). While elements of the funerary practices show influences from the Elbe, North Sea, Thuringian and Alemannic areas, it is still unclear if this indicates the arrival of newcomers or if mainly local communities – perhaps together with newcomers – developed this new mortuary practice.

In order to understand these processes, the isotopic analysis of strontium, oxygen and carbon from human tooth enamel will be used to differentiate between migrant and local individuals. Furthermore, several faunal, soil and water samples will be analysed to determine the biologically available strontium signature of each site and the region. The isotopic results of human individuals in combination with the archaeological and anthropological data will be evaluated concerning the integration and separation of migrant individuals within burial communities, as well as the reflection of “foreignness” in the material culture. In addition, changes in mobility patterns during the formative time of the Early Middle Ages between the late 5<sup>th</sup> and

6<sup>th</sup> centuries and how this is connected to the overall socio-political events will also be investigated. One focus of the study concentrates on the question of whether communities local to the Upper Rhine Valley were involved in the creation of the new funeral rite and to what extent foreign objects, mainly hand-made pottery, are indicators of the presence of immigrants. The results from the three cemeteries under investigation will be compared in order to evaluate whether similar processes and influences shaped these burial communities.

### *Structure of the thesis*

The dissertation is divided into four chapters. The first chapter consists of an introduction to several fundamental topics of the thesis and is separated into two parts. The first part summarises the events of the 5<sup>th</sup> and 6<sup>th</sup> centuries in northern Gaul which are known from the written sources, including the rise of the Franks, the end of the Western Roman Empire and the Merovingian conquests in the 6<sup>th</sup> century. This is necessary because interpretations concerning the row-grave cemeteries are often based on these vague historical events. This is followed by a description of the historical and archaeological evidence for the Upper Rhine Valley, in order to obtain a picture of the settlement and demographic structure of this region in the 5<sup>th</sup> and 6<sup>th</sup> centuries. The second part introduces the biogeochemical basics of isotope research for mobility studies and explains the use of oxygen, carbon and strontium isotope analysis for the identification of migrants. It also describes the structure of tooth enamel and process of enamel mineralisation.

The second chapter starts with a general description of the research area, the northern Upper Rhine Valley, including natural and biogeochemical conditions and a brief assessment of the few biogeochemical studies conducted in this region so far. This is followed by a description of the sites from which human dental enamel was analysed, including location and natural conditions, research history, occupation history and cultural interpretation. It also includes the research questions and the sampling strategy for each site. This chapter concludes with a description of the methodology related to enamel sampling and stable isotope analysis.

The third chapter presents the results of the isotope analyses, followed by the discussion in the fourth chapter. The discussion starts with an evaluation of the local biogeochemical signatures of the research area, which is the basis for the interpretation of the human data. In the following part, the results of the isotope

analyses from the different sites are evaluated with regards to the respective research questions. The thesis ends with a final conclusion about human mobility and cultural diversity in the early medieval Upper Rhine area, referring to the historical and archaeological evidence. Final remarks recapitulate the new information generated by this research project.

# **1 Archaeological and historical background**

## **1.1 General historical overview**

In the following, a general historical overview about the events of the 5<sup>th</sup> and 6<sup>th</sup> centuries in Central and Western Europe which are known from the written sources will be provided in order to understand the overall socio-political situation which resulted in the creation of a new funeral rite in the late 5<sup>th</sup> century. The review focuses on the Franks of the Merovingian dynasty, which governed over large parts of Central and Western Europe, including the Upper Rhine Valley when the new mortuary practice tentatively commenced and further developed into the typical row-grave cemeteries.

### **1.1.1 The rise of the Franks and the end of the Western Roman Empire**

The term Franks is first attested in Roman written sources since the middle of the 3<sup>rd</sup> century mainly in connection with raids against the Roman Empire and was used for different non-Roman groups living in the north and east of the Lower and Middle Rhine (James 1988, 35; Nonn 2010, 11–15; Ewig 2012, 9). The origin and structure of these Frankish confederations is unknown (Ewig 2012, 10). Beside raids into the Roman Empire, which are attested for the following two centuries, written sources indicate that Franks as well as other non-Roman groups, which were defeated by Romans, were settled within the Roman Empire and served as soldiers, soldier peasants and farmers (Nonn 2010, 36–54; Ewig 2012, 11). The Salian Franks, for example, were allowed by the Romans to settle in Toxandria, a de-populated region supposed to be located between Meuse and Scheldt (James 1988, 51; Nonn 2011, 50–51; Ewig 2012, 11). In the 4<sup>th</sup> century, the involvement of Franks in the Roman army included not only the recruitment of individuals or auxiliary regiments but even went so far that some of them started a military career and also ascended to the highest military ranks (James 1988, 41–44; Nonn 2010, 54–57; Ewig 2012, 11). This ambivalent Frankish-Roman relationship between offence and defence persisted also in the first half of the 5<sup>th</sup> century. Thus, Frankish groups defended the Roman Empire against non-Roman groups such as Vandals, Alans and Sueves which crossed the Rhine in 405/406 or 406/407 (Nonn 2011, 69–70; Ewig 2012, 12). However, Frankish

groups were likely responsible for repeated attacks against the Roman city of Trier in the first half of the 5<sup>th</sup> century (Nonn 2011, 74–76). Furthermore, it is mentioned that Franks located at the Rhine occupied a region on the left side of the Rhine around Cologne and Xanten. Aëtius, military commander of the Western Roman Empire, reclaimed the captured region in 428 but allowed the Franks to settle in return for military service some years later. The date of this settlement of Frankish groups in the region around Cologne is unclear but it seems to have taken place around 436 (Nonn 2010, 77–79; Trier 2011, 177; Ewig 2012, 12). The Salian Franks, who settled in Toxandria in 358 and took over the leadership of the Franks at the end of the 5<sup>th</sup> century, were mentioned in the written sources again only after 440 in connection with raids into the Belgica II, headed by a king named Chlodio. It is reported that Frankish groups under Chlodio conquered regions around Tournai and Cambrai and expanded the territory to the Somme. Aëtius defeated them in the middle of the 5<sup>th</sup> century but allowed them to settle in the previously conquered areas (Nonn 2011, 79–84; Ewig 2012, 13). Furthermore, it is mentioned that in 451, Frankish groups fought alongside Aëtius in the Battle of the Catalaunian Fields against Attila, who in turn was supported by Franks from the right side of the Rhine (Nonn 2010, 84–89; Ewig 2012, 14).

A turning point for the rise of the Franks and the decline of Roman power in the northeastern provinces was the death of the commander Aëtius in 454 and the emperor Valentinian III in 455 (Nonn 2011, 69; Ewig 2012, 14). The following years until the final demise of the Western Roman Empire was characterised by a rapid succession of weak emperors with power that was primarily exercised by military commanders (Nonn 2011, 95–95; Ewig 2012, 15–16). As a consequence of this unstable time, Franks from the right side of the Rhine expanded into parts of the provinces of Germania (I and II) as well as Belgica (I and II) in the middle of the 5<sup>th</sup> century. The precise regions and impacts are unknown. It is debated if the region around Mainz was also included in the sphere of the Rhenish Franks (Nonn 2011, 90). Around 460, Cologne was finally under Frankish control. Trier was also attacked, and even temporarily occupied, but still remained under Roman administration by a *comes* Arbogast in the 470s (Nonn 2010, 90–92; 103–107). Alemanns, a conglomeration of various barbarian (warrior) groups led by their own chiefs in the area east of the Rhine, also started raids into the Roman Empire. If Alemanns indeed settled on the

western bank of the Upper Rhine Valley remains disputed (Geuenich 2005, 75–77). Furthermore, other non-Roman groups which already settled within the Roman Empire under their own kings since the first half of the 5<sup>th</sup> century, such as the Visigoth in Aquitaine and the Burgundians in the region Sapaudia, made attempts to expand their territories (Nonn 2012, 96; Ewig 2012, 15). A further stride towards the end of Roman impact over Gaul was the refusal of Aegidius, the military commander in Gaul who was deposed in 461, to accept the authority of the new emperor. Aegidius managed to assert his position as an independent Roman ruler north of the Loire and was succeeded around 469 by his son Syagrius, the last official Roman ruler in Gaul (Nonn 2012, 95–96; 108; Ewig 2012, 15).

In the following years, the Western Roman Empire ended by law with the removal of the last Western Roman emperors in 476 and 480. Those striving after power at that time were, apart from Roman military commanders, also non-Roman rulers, including kings of the Visigoths and Burgundians but also high military persons of Frankish origin such as Arbogast in Trier or Childeric in Belgica II. This was the time when the Merovingians came into play.

### **1.1.2 The Merovingians and their conquests**

Childeric is the first attested Merovingian ruler of the Salian Franks in Gaul and is historically documented since 463 in connection with battles against the Visigoths and Saxons, mainly in the Loire region. During the gradual collapse of the Western Roman Empire in the 460–70s, he was the administrator of the Roman province Belgica II in northeastern Gaul (James 1988, 75; Wood 1994, 38; Halsall 2007, 270; Becher 2011, 131–132). Childeric died in 481/82 and was buried at his residence in Tournai. His grave was discovered in 1653 with precious objects, including a seal ring with the inscription *Childirici regis* which revealed his identity. The grave offerings show that he had strong connections to the Roman Empire and reflect, on the one hand, his position as Roman commander and, on the other hand, as a Salian ruler (James 1988, 40; Nonn 2010, 97; Becher 2011, 132–138; Ewig 2012, 16–17). Childeric was succeeded by his son Clovis as ruler of the Salian Franks and administrator of Belgica II (James 1988, 41; Wood 1994, 41; Geary 1996, 88; Becher 2011, 144; Ewig 2012, 18). During Clovis' reign, he destroyed the political



independence of many tribes, and as a king/warlord of the Franks he led his people into a series of successful military campaigns that made the Franks one of the most powerful of the barbarian groups. In 486/487, Clovis started his conquest and defeated Syagrius, the last “Gallo-Roman” military leader in northern Gaul, and extended the Merovingian territory to the Loire (James 1988, 79; Geary 1996, 89; Becher 2011, 144–152; Ewig 2012, 20). Other military campaigns were conducted against the Alemanns in 496 and 506 where they were finally defeated. The Alemannic settlement area east of the Rhine was now under Frankish sovereignty (Geuenich 2005, 18–23; Steuer 2012, 72–74; Ewig 2012, 21–22). This was also the time when the regions around Worms and Speyer were ultimately integrated into the Frankish territory (Ewig 2012, 24–25). In 507, Clovis attacked the Visigoths with the help of the Burgundians and the ruler of the Frankish kingdom at the Middle Rhine (Halsall 2007, 306; Ewig 2012, 25–28). In his last years between 508–511, maybe already around 490, Clovis was focused on the elimination of his relatives and other Salian and Rhenish kings in order to establish his autocracy in the Merovingian kingdom which extended from the Rhine in the northeast to the Garonne in the southwest. When Clovis died in 511, the kingdom was divided among his four sons Theuderic, Chlodomer, Childebert and Clothar. The eldest son Theuderic gained the eastern part of the kingdom such as the regions around Trier, Mainz, Cologne, Basel and Châlons as well as the freshly conquered regions on the eastern side of the Rhine (Ewig 2012, 32; Hartmann 2012, 24). The first military campaign by Childebert and Clothar was fought against the Burgundian kingdom which was successfully conquered in 534 (Wood 1994, 52; Geary 1996, 122; Ewig 2012, 35). Theuderic focused on right-sided areas of the Rhine and started a battle with Clothar and Saxon groups from the North Sea area against the Thuringian kingdom around 530 (Ewig 2012, 34). Theuderic conquered the regions around the Saale, Middle Elbe and Main Rivers and gave the area north of the Unstrut River to the Saxons (Ewig 2012, 34). In the meantime, Childebert conducted a campaign against the Visigoths and extended the border towards the Pyrenees (Ewig 2012, 35). Theuderic, who died in 533, instructed his son Theudebert, who inherited his father’s territories, to conquer southern Aquitaine which was successful in 532/533 (Ewig 2012, 36). While Childebert obtained the Provence, the last phase of expansion was restricted to Theudebert who consolidated his position north of the Alps in Rhaetia as well as the two Noric provinces towards

the border of Pannonia in 540 and 545. To protect the border, he formed alliances with the Langobards and Gepids. In 545, he sent troops to Venice where they took control over the area to Treviso/Vicenza (James 1988, 94–98; Ewig 2012, 37–40). In 558, Clothar inherited the territories of his deceased relatives which allowed him to reunite the Frankish kingdom until his death in 561 (Ewig 2012, 40–41). The borders of the Merovingian kingdom remained stable until the end of the Merovingian period at the beginning of the 7<sup>th</sup> century, with the exception of the areas in northeastern Italy and the southern Noric province which fell back to the Byzantine Empire (Ewig 2012, 40–41).

### **1.2 The 5<sup>th</sup> and 6<sup>th</sup> centuries in the northern Upper Rhine area**

The written sources informing about the overall socio-political events in the 5<sup>th</sup> and 6<sup>th</sup> centuries have shown that these were times of profound changes in Europe. In contrast to regions more inland, the borderlands at the Rhine River were certainly more affected by these processes especially concerning demographic dynamics. In the following, the historical sources and archaeological evidence informing about the 5<sup>th</sup> and the early 6<sup>th</sup> century in the Upper Rhine Valley will be discussed. This is necessary in order to assess the demographic structure of this region as well as to what extent the transition from the Late Roman to the Early Medieval period was a break or rather a continuous change. The late Roman times of the first half of the 5<sup>th</sup> century will be included in these considerations because otherwise it is not possible to fully understand the processes that led to the events in the second half of the 5<sup>th</sup> and the early 6<sup>th</sup> centuries.

#### **1.2.1 Historical evidence**

There are, in general, only few and vague written sources which inform about the situation in the Upper Rhine Valley in the 5<sup>th</sup> and 6<sup>th</sup> centuries. They are mainly dealing with topics concerning the end of the Roman military and civil administration as well as the presence of non-Roman groups such as the Burgundians and Alemanns in this region (Fesser 2006, 16). It is generally accepted that the Roman military presence at the northern Upper Rhine border did not end with the “invasions” of several non-Roman groups across the Rhine into the Western Roman Empire on the

night of New Year's Eve in 405/406 or 406/407 which is mentioned in several written sources (Kulikowski 2000; Scharf 2005; Fesser 2006, 18; Grünewald 2004, 126–127; Castritius 2009, 35–38). This is also supported by the *Notitia Dignitatum*, an official register of all Roman civil and military posts of the Eastern and Western Late Roman Empire (Fesser 2006, 16). One of the 90 chapters is about the *Dux Mogontiacensis*, the commander of the Middle and Upper Rhine, residing in Mainz and controlling eleven military stations between Selz in the south and Andernach in the north (Oldenstein 1992; Scharf 2005, 1; 9). In recent studies, it was supposed that the register of the *Dux Mogontiacensis* was written in the early 5<sup>th</sup> century or at the beginning of the years around 420, implying persistence of Roman military administration of the northern part of Germania I until at least 420/30 maybe with the help of Burgundian federates (Oldenstein 1992; Kaiser 2004; Scharf 2005). The presence of Burgundians in the Upper Rhine Valley between 406/413 and 436 is a highly disputed topic (Wackwitz 1964; Knöchlein/Rupprecht 1998; Grünewald 2004; Grünewald 2006; Grünewald 2009; Castritius 2009; Böhme 2012). Based on few written snippets, it was reconstructed that at a time after the “invasions” between 406 and 413 a Burgundian group of warriors from the eastern side of the Rhine entered the Roman Empire under their own leader (Martin et al. 2008, 242–243; Castritius 2009, 38; Jung 2012, 74; Schipp 2012, 62–64). Most researchers assume that the presence of Burgundians on the western bank of the Rhine was legalised by contract with one of the usurpers of that time or at latest under Aëtius which allowed them to settle in return for military service (Wackwitz 1964, 48–49; Kaiser 2004, 27; Scharf 2005, 146; Castritius 2009, 39; Schipp 2012, 63). For the year 435/36, Burgundians are mentioned in the written sources with raids into the province of Belgica which resulted in penalties that were executed by Hunnic auxiliary troops by order of Aëtius. A few years later, in 443, the remaining Burgundians were resettled into the region *Sapaudia* near Lake Geneva (Kaiser 2004, 32–34; Castritius 2008; Jung 2012, 74; Schipp 2012, 65).

The crossing of the Rhine by Hunnic troops under Attila in 451 had no discernible effects on the Upper Rhine Valley. The border was still allocated by troops in the middle of the 5<sup>th</sup> century which is attested by the last inspection of the military commander and afterwards Roman emperor Avitus in the year 455. However,

this marks the beginning of the end of Roman influence on the Rhine border (Bernhard 1997, 12).

The second half of the 5<sup>th</sup> century is a special research problem in the northern Upper Rhine Valley. Two written sources were mainly used to describe the socio-political situation of the region. These are a panegyric of the Saint Sidonius Apollinaris and the Ravenna Cosmography compiled by an anonymous author in Ravenna. The informative content, reliability, and interpretation of both resources are highly disputed under historians and archaeologists (Bernhard 1997, 8). The panegyric of the Saint Sidonius Apollinaris for the emperor Avitus is the primary text which led some researchers to conclude that Alemanns settled on the western side of the Upper Rhine Valley during the second half of the 5<sup>th</sup> century. A passage referring to the year 455 describes raids of the Franks into Roman provinces as well as efforts of the Alemanns to make a foray into the Rhine area (Knöchlein 2003, 137–138; Fesser 2006, 41–42). This section of the text was often interpreted such that the left bank of the Rhine, around the region of Worms, was occupied by the Alemanns around 455, and that this settlement was legalised by contract by the military commander Avitus, who had inspected the Roman Rhine border in the same year (Ewig 1979, 278–279; Grünewald 1996, 160). Other researchers exclude a permanent Alemannic settlement on the western side of the Rhine and assume rather short raids without sustainable effects (Wieczorek 1996, 242; Martin 1996, 167; Knöchlein 2003, 137; Lange 2004, 237) and still other researchers suspect the presence of Alemanns among the settlers of the second half of the 5<sup>th</sup> century even if they are meagre in number (Engels 2005a, 328–331; Fesser 2006, 43–44; Grünewald/Koch 2009, 82; Engels 2012, 210–212).

The second source used to examine the presence of the Alemanns is the Ravenna Cosmography. This work is a description of the world and consists of a list of place-names from India to Ireland and was written by an unknown author in Ravenna during the 8<sup>th</sup> or 9<sup>th</sup> century. It is supposed that information contained in this work derived from sources from the time around 500, but this is still controversial (Springer 1998; Fesser 2006, 44–45; Nonn 2010, 93; Ewig 2012, 16). The author mentioned in his descriptions that Mainz was situated in the Frankish area, while Worms was the last place which belonged to the Alemanns (Fesser 2007, 44). Despite the fact that not only the date of the described situation is uncertain but also the

primary information that the author has chosen, the *Cosmography* is still often used as proof of an Alemannic settlement on the western side of the Rhine or that the region was an Alemannic military controlled influence or tribute zone which was not necessarily connected with immigrations of people from Alemannic areas (Staab 1975, 12; Ewig 1979, 279; Staab 1996, 238; Wiczorek 1996, 241–242; Knöchlein 2003, 137–138; Geuenich 2005, 71; Fesser 2006, 44–45; Nonn 2010, 93–94; Ewig 2012, 16). Additionally, there is disagreement about the time when this Alemannic period should have taken place. Some authors assume a relatively long period between the pull-out of the Burgundians and the surrender of the Alemanns before the Franks at the end of the 5<sup>th</sup> or the beginning of the 6<sup>th</sup> century in the form of a long-term settlement (Ewig 1979, 279–280; Grünewald 1996, 160; Fesser 2006, 47–48; Grünewald/Koch 2009, 82). Others define the described division only in the time frame between approximately 496 and 506. After this approach, the Alemannic forays described by Sidonius were only concentrated on right-sided regions of the Rhine between Lahn and Neckar while the Frankish raids were concentrated in the Upper Rhine Valley. Based on an alliance between Rhenish Franks and Gondioc – military commander of Gaul and king of the Burgundians – in 463, Alemannic groups were hindered from entering the left-sided region of the northern Upper Rhine area. The right to settle in the Upper Rhine Valley was therefore rather granted to the Rhenish Franks than the Alemanns (Staab 1975, 12; Staab 1996, 238; Wiczorek 1996, 242; Knöchlein 2003, 137–138).

For the following decades, the written sources remain silent about the socio-political situation in the Upper Rhine Valley. Based on the historical information described above, it is known that at the beginning of the 6<sup>th</sup> century, the region was under the influence of the Salian Franks or rather the Merovingians, namely Clovis, who bequeathed the eastern regions of the kingdom, including the Rhine areas, to his son Theuderic in 511.

### **1.2.2 Archaeological evidence**

In the following, the archaeological remains from the urban centres, the military stations as well as the rural areas on the western bank of the Upper Rhine Valley of the 5<sup>th</sup> and the beginning of the 6<sup>th</sup> century will be presented. The intention is to get an

overview about the settlement and demographic structure of this time. These investigations focus on the proof of continuity between late Roman and early medieval times as well as the presence of foreign individuals and groups in the Upper Rhine Valley.

### *1.2.2.1 Chronological aspects*

The 5<sup>th</sup> century marks the important transition from the Late Roman to the Early Medieval period in the Upper Rhine Valley. The few archaeological remains dating between 400 and 500, especially compared to the relative abundance of remains from the 4<sup>th</sup> or the 6<sup>th</sup> century, suggest reduced settlement activity in the northern Upper Rhine Valley. The low visibility of the 5<sup>th</sup> century archaeological remains is compounded by the poor state of archaeological research, including the lack of modern excavations, reprocessing of old excavations, and the absence of secure datable objects such as copper coins whose production declined at the beginning of the 5<sup>th</sup> century. However, based on recent research on material culture, especially ceramic and glass vessels, it is possible to divide the Late Roman period in the Upper Rhine Valley provisionally into three chronological horizons (Bernhard 1997, 9–11; Bernhard 2007, 117; Bakker 2012). The first horizon dates roughly from 370 to 410 and is characterised by material typical for the fort Altrip. These are mainly Argonne ware, grey Nigra ware and coarse ware most often from Mayen workshops. The second horizon from around 410–430/40 is based on material which is typical for the second period of the fort Alzey such as Argonne ware with white painting and other late types as well as wheel-decorated ware. The last horizon from around 430/40–460 is characterised by special red-painted ware and certain glass vessels (Bernhard 2007, 117).

In the second half of the 5<sup>th</sup> century, a new archaeological period is initiated in the Upper Rhine Valley – the Early Middle Ages or Merovingian period. As the earliest graves already start before the take-over of the Franks, the term proto-Merovingian was proposed for graves of the second half of the 5<sup>th</sup> century (Ament 1992, 41; Fehr 2010, 726). In the rural areas of the regions Rhine Hesse and Palatinate, this period is identified with the foundation of new settlements and cemeteries which have no direct connection to late Roman structures. The main archaeological sources are human graves, and only few settlements have so far been

identified and investigated. Most of the burial places are situated at the fringes of modern villages. The early medieval settlements were the precursors of the present-day villages and have been largely destroyed in the scope of later building activities. The cemeteries are also called “row-grave cemeteries”. The term is an ideal type which is defined by several characteristics such as inhumation, east-west orientation of the graves, location outside but nearby a settlement, a long, continuous occupation and especially richly furnished burials (Ament 2003, 362–365). Although not all characteristics are equally applicable to all sites, the term is used to describe a huge number of graveyards dating between the second half of the 5<sup>th</sup> and the middle of the 8<sup>th</sup> century in Western and Central Europe. Based on the numerous funerary artefacts which were used to demonstrate prestige and social conditions (Brather 2007, 124; Fehr 2010, 725–783), several chronology systems have been developed for the Rhine-Moselle area and Southwest Germany (Böhner 1958; Neuffer-Müller/Ament 1973; Siegmund 1998; Koch 2001; Müssemeier et al. 2003). The most recent publications of cemeteries, the sites of Dirmstein, Eppstein and Hechtsheim in the northern Upper Rhine Valley (Leithäuser 2011; Engels 2012; Koch 2012a), are based on the chronology model of Southern Germany which was developed at the cemetery of Pleidelsheim in Baden-Württemberg (Koch 2001, 43–88). This model is also used in this study (Tab. 1.1).

**Tab. 1.1. Chronological system.**

	<b>Koch 2001</b> (SD = SüdDeutschland)	
<b>Proto- Merovingian</b>	SD-phase 2	~460–480
<b>Early Merovingian</b>	SD-phase 3	~480–510
	SD-phase 4	~510–530
<b>Middle Merovingian</b>	SD-phase 5	~530–555
	SD-phase 6	~555–580
	SD-phase 7	~580–600

#### 1.2.2.2 Urban settlements and military stations

The inner structure of Mainz, *the metropolis civitas Mogontiacensium*, for the latest Roman period since 400 is unknown (Knöchlein 2011, 276). From the three probably

continuously occupied cemeteries from the Roman to the Merovingian period outside the Roman town wall only few graves and single finds are known which date to the period between 400 and 450/460 (Knöchlein 2011, 276). Two graves were discovered in the northern cemetery St. Peter. The first grave dating around the middle of the 5<sup>th</sup> century contained a spatha, axe, belt buckle, bell beaker as well as a comb with a triangular grasp. The neighbouring grave 2, which is older than the first grave but still dates to the first half of the 5<sup>th</sup> century, contained a late Roman belt buckle, arrow heads as well as a knife with silver and golden inlays (Bernhard 1982, 97–98; Knöchlein 2011, 276). The graves are interpreted as soldier graves which were members of a military unit either under Roman authority or as federates under their own leader, engaged in protecting the border (Bernhard 1982, 98). No Merovingian burials are known for this area but the secondary use of grave plates with inscriptions of the 6<sup>th</sup> and the 7<sup>th</sup> centuries is seen as proof for the continuous occupation of this burial place (Knöchlein 2011, 276). In the area of the modern main cemetery, a silver belt buckle with a special pin was found which dates to the latest Roman period (Bernhard 1982, 98; Knöchlein 2011, 276). This single find lies chronologically between the late Roman and the Merovingian graves (Knöchlein 2011, 276). From the southern cemetery St. Alban, only a single find of a belt buckle with a chip-carved decoration of the type Herbergen was recovered which dates to the latest Roman period as well as a grave plate of the same time which was in secondary use. No burial remains of the Merovingian period were found in this cemetery except stone plates with inscriptions of the 6<sup>th</sup> and 7<sup>th</sup> centuries which may indicate a continuous occupation (Knöchlein 2011, 277–278). A separate Merovingian cemetery dating between the 6<sup>th</sup> and the 8<sup>th</sup> centuries was found in the vicinity of this place (Knöchlein 2011, 278). Some single finds are also known from the town centre. These include a crossbow fibula found close to the inner fort, a silver buckle with a chip-carved decoration from the Rhine as well as a punched decorated belt fitting from the area in front of the theatre which are typical for the time after 400 (Knöchlein 2011, 276). The earliest date for the two treasure troves found in the town area as well as near the bridge head in Kastel on the right side of the Rhine is 407 and it is considered that the troves were deposited as a result of the historical event of 411 (Bernhard 2007, 123; Knöchlein 2011, 276). However, due to the long minting period of the Honorius coin from the treasure trove from Kastel, it is also probable that it was deposited after 423



(Bernhard 1982, 98). A recovered shipwreck was dated between 421 and 441, most probably around 431 and a wooden pile structure of a house was <sup>14</sup>C-dated between 400 and 530, most probably to the middle of the 5<sup>th</sup> century (Knöchlein 2011, 276). In addition, further finds, such as metal objects, glass, bone and pottery, indicate that the area within the town wall was settled during the 5<sup>th</sup> as well as in the 6<sup>th</sup> and 7<sup>th</sup> centuries (Knöchlein 2011, 282; 280, Fig. 5). Based on the distribution of the finds, it is likely that during the Merovingian period, the concentration of the settlement was reduced to the area close to the Rhine (Knöchlein 2011, 281). However, the finds from the 5<sup>th</sup> and 6<sup>th</sup> centuries are still very rare to suffice as proof of a structural continuation from the Late Roman to the Early Medieval period (Knöchlein 2011, 281). Nevertheless, based on some archaeological finds and evidence, it is assumed that Mainz was starting to evolve an important clerical and economic role already in the 6<sup>th</sup> and 7<sup>th</sup> centuries (Knöchlein 2011, 282). Late Roman finds from known Roman settlements directly connected to the town Mainz, such as Dimesser Ort and Weisenau, are unknown yet. Probably from Weisenau but without context is a fibula of the type Niederflorstadt-Wiesloch which dates from approximately 450–460 (Knöchlein 2011, 276). The Frankish predecessor settlement of modern Weisenau was founded in the 6<sup>th</sup> century. The Merovingian burial place in the vicinity of Dimesser Ort has yielded finds of the 7<sup>th</sup> and the 8<sup>th</sup> centuries but the find of special lances indicate an earlier foundation (Knöchlein 2011, 276). The suburban and rural areas around Mainz have not yet revealed signs of a continuation of settlements after 400. However, some ceramic finds similar to those of the fort Alzey may indicate a settlement during the 5<sup>th</sup> century. The present state of research is still poor and it is not assumed that the nearer surrounding of Mainz was depopulated (Knöchlein 2011, 276).

In Worms, remains of Argonne and coarse ware from Mayen outside and inside the walls of the Valentinian fort as well as a find of a North African Sigilatta sherd from the second half of the 5<sup>th</sup> or the last third of the 5<sup>th</sup> century are seen as proof that Worms was inhabited by civil and military persons until around the middle of the 5<sup>th</sup> century (Grünwald/Wieczorek 2012, 12). No remains of a destruction horizon which may be connected to the historical events, such as the crossing of the Rhine or the “Burgundian kingdom”, have been found (Grünwald/Wieczorek 2012, 12). The large Roman cemeteries along the outward roads yielded numerous finds of

the Late Roman period, including several finds with “Germanic” influences (Bernhard 1982, 90–95; Grünewald 2008, 195). However, after the middle of the 4<sup>th</sup> century the tradition of placing grave goods ceased and only few single finds can be dated to the 5<sup>th</sup> century (Bernhard 2007, 121). It is often speculated that the graves without grave offerings are the burials of late Roman provincial communities (Grünewald/Hahn 2006, 86–88; Grünewald/Wieczorek 2012, 12). However, several grave stones with Germanic names written in Latin are found and some of them, such as the grave of Pauta or Ludino, date to the first and second third of the 5<sup>th</sup> century respectively (Boppert/Wieczorek 1996, 870–871; Grünewald 2008, 195; Grünewald/Koch 2009, 200–202; Grünewald/Wieczorek 2012, 12). One of the few finds is a belt fitting from a grave near the Liebfrauenkirche which is dated to the late 4<sup>th</sup> and the early 5<sup>th</sup> century and is supposed to be typical for a military person of “Germanic” origin (Bernhard 1982, 95). Furthermore, two brooches were found in an ash- and bone heap in the southern cemetery Maria Münster. One of these, a bronze cross-shaped fibula, was identified to be of Saxon type from the middle of the 5<sup>th</sup> century and the evidence was interpreted as a “Germanic” cremation burial from the middle to the second half of the 5<sup>th</sup> century (Grünewald/Hahn 2006, 166; 180). Except the finds of few red-painted sherds, which cannot be dated exactly to the 5<sup>th</sup> or 6<sup>th</sup> centuries, as well as further single finds of coins and Argonne ware, there is an absence of archaeological remains in the town area of Worms between the time of the assumed end of the Western Roman administration around 455 and the beginning of the Frankish influence at the beginning of the 6<sup>th</sup> century (Grünewald 1996, 160; Bakker 2001, 27–41; Bakker 2012, 7; Grünewald/Wieczorek 2012, 14). Finds dating to the 6<sup>th</sup> century are more numerous. However, remains from the Merovingian period within the town wall are rare and settlement structures have not been found yet (Grünewald/Koch 2009; 91; Grünewald/Wieczorek 2012, 14–15). Most of the early medieval remains are known from graves which were placed at the fringes of the Roman cemeteries outside the town wall (Grünewald 1996, 162). At the Schillerstraße cemetery in the north of Worms several graves are known which are from old excavations and mainly from destroyed contexts, but it is assumed that the complete cemetery was recorded (Grünewald/Koch 2009, 98–195). The oldest graves, two soldier graves, date to the SD-phase 4, the first third of the 6<sup>th</sup> century (Grünewald/Koch 2009, 169–170; 194). It is striking that the oldest graves are not in direct connection with the late Roman

graves and it is excluded that there was a continuous occupation (Grünwald/Koch 2009, 194–195). Several precious objects show that a wealthy community interred their deceased at the cemetery (Grünwald/Koch 2009, 195). A further cemetery was located at the eastern section of the Mainzer Straße. The known graves date to the SD-phase 7 and therefore a continuous occupation can be proven (Grünwald/Koch 2009, 209). To the north part of the Kapuzinerstraße, a small group of graves was detected where four grave stones were recovered. Except the grave of Pauta which was already mentioned, the grave stones and inscriptions date to the time after 500 (Grünwald/Koch 2009, 198–203). Further to the north at the southern part of the Kiesstraße, several early medieval graves indicate the presence of a further settlement but the graves are not exactly datable (Grünwald/Koch 2009, 196). In the western part of Worms on the Andreasstraße, an early medieval grave with an *ango*, a special type of lance, was detected which can be dated to the 6<sup>th</sup> century probably to the SD-phase 6 (Grünwald/Koch 2009, 214–217). At least two cemeteries were known from the southern area of Worms. The supposed grave interiors of Maria Münster date to the 6<sup>th</sup> century (Grünwald/Koch 2009, 224). From the site of Bollwerk in 1903, six graves were detected which date to the SD-phase 5 and are not associated with the Roman graves (Grünwald/Koch 2009, 226–235). Based on the special and precious grave goods, it is supposed that these are the remains of a wealthy family; probably from Middle Germany (Grünwald/Koch 2009, 234).

In Speyer, civil buildings have been excavated with several finds which verify the settlement until the 460/470s. The settlement within the wall of the fortification was also probably continuous until the Early Middle Ages (Bernhard 1997, 86–94). Destruction horizons, which may be ascribed to historical events such as the crossing of the Rhine, the Burgundian occupation or the Hunnic invasion, were not found in the archaeological record (Bernhard 2007, 119). The four late Roman cemeteries along the outward cemeteries were reduced to one cemetery (St. German). The burials are mainly ordinary graves without grave goods. The few graves with objects include a burial of a soldier with a belt buckle of the early 5<sup>th</sup> century, a grave with a drinking service from around 450 and a burial with a shoe buckle typical for the time after 450. A burial of a child in a North African amphora of the 5<sup>th</sup> century show, on the one hand, trade links and, on the other hand, that there was enough purchasing power at that time. The cemetery has only partially been excavated, but it still seems that the

population density was relatively high during the 5<sup>th</sup> century (Bernhard 2007, 119). Objects such as a crossbow brooch, a small lugged neck ring and a special ceramic vessel are seen as proof of “Germanic” influences during the Late Roman period (Bernhard 1999, 20). A total of 170 Merovingian graves have been excavated which date to the second quarter of the 6<sup>th</sup> century. However, it is assumed that the burial place was continuously settled since the Roman period. The detected graves, especially the numerous and precious grave goods as well as burial mounds and horse graves, show the wealth of these families. Two further cemeteries (Burgfeld, Baumwollspinnerei) date to the second half of the 5<sup>th</sup> century but are discontinued already in the 6<sup>th</sup> century. The settlement of Altspeyer was founded in the 6<sup>th</sup> century. The connected cemetery included graves of the 6<sup>th</sup> and 7<sup>th</sup> centuries. The settlement Vogelsang/Winternheim is located in the southern suburb of the town and was not completely excavated, but a total of around 160 pit houses and 112 other features were recovered. The investigation of the ceramics has revealed that the settlement was in use for over 750 years and that during the whole occupation time the location was relocated from the east to the west. The settlement starts with a house which dates to the end of the 5<sup>th</sup> century and lasts until around 1200. Finds of pottery show parallels to the northern German coastal area and it is assumed that the settlers originated from this region (Bernhard 1997, 95).

The best investigated Roman fort of the region is situated in Alzey around 30 km from the Rhine River. Excavations have revealed at least three construction periods (Oldenstein 1992, 156–281; Gupte/Haupt 2006, 149–153). The fort was built around 369/370 and is interpreted as an accommodation for the Comitatus mobile forces for the protection of the hinterland (Oldenstein 1992, 282). Some parts of the fort were destroyed and the connected coins give a *terminus post quem* around the 380s (Oldenstein 1992, 196–197; 282–283). However, it is assumed that the end of this first construction period is connected with the historical events of 405/406/407 or 411/413 (Oldenstein 1992, 282; Bernhard 1997, 10; Bernhard 2007, 122; Gupte/Haupt 2006, 152). The second period is characterised by rebuildings and newly constructed buildings, including pit houses and can be dated archaeologically only roughly to the first half of the 5<sup>th</sup> century (Oldenstein 1992, 284–286; Gupte/Haupt 2006, 152). However, based on written sources this period is again connected with the presence of Burgundians (Oldenstein 1992, 340–347). Therefore, it is supposed that

the second period started after 405/406/407, probably around 412/413, and ended after 425 with an intentional infilling of the wells and defensive ditches (Oldenstein 1992, 279–280; Bernhard 2007, 122). This is viewed as a sanction of the Romans in order to destroy the fortified character of the fort and is connected with the historical event around 436/443 (Oldenstein 1992, 345–347; Bernhard 2006, 166; Bernhard 2007, 122). “Germanic” finds from the inner part of the fort, such as combs with three layers and bell-shape grasps, date around 400 and the first half of the 5<sup>th</sup> century (Bernhard 1982, 99; Theune 2004, 96–97; Klenner 2006, 107). A grave with weapons from a cemetery outside the fort was classified in the context of the non-Roman crew of the fort but it most probably dates to the end of the 3<sup>rd</sup> or beginning of the 4<sup>th</sup> century (Bernhard 1982, 99; Theune 2004, 96–97; Klenner 2006, 107). After Oldenstein, the last period dates at the earliest after 425 and the middle/second half of the 5<sup>th</sup> century (Oldenstein 1994, 286; 348). As the constructions of the last period are in Roman military tradition, Oldenstein speculates that the inhabitants are possibly the last try of the Western Roman Empire to protect the border and that the period ends with the decline of the Roman authority around 455 (Oldenstein 1994, 281; 348–350). Newer excavations of the year 2002 have not uncovered evidence that verifies the settlement after 440. Furthermore, they divide the “Germanic” second period into two parts with a cut in the 420s (Gupte/Haupt 2006, 152–153). The absence of Argonne ware with Christian motives, which is typical for the middle of the 5<sup>th</sup> century, is considered as proof that there was a lack of purchasing power of a military community and as an argument against the idea of Roman military defence in the second third of the 5<sup>th</sup> century (Gupte/Haupt 2006, 153). However, they do not exclude the presence of people in an early Christian rather than in a military context because of the finds of a bread stamp, early Christian grave stones and a building that is assumed to be a late Roman fort church (Gupte/Haupt 2006, 153; Bernhard 2007, 122). However, the dating of these early Christian pieces of evidence is problematic (Boppert 2006, 87–95). The general problem with the dating of the three periods is that they are mainly based on historical events. At least three late Roman sporadically excavated cemeteries are known from Alzey. None of the graves date to the 5<sup>th</sup> century or can be seen in a military context. Just as a result of the topographical situation, one of the cemeteries may be connected to the Roman fort (Klenner 2006, 105–113). A piece of

wheel-decorated Argonne ware outside the fort dates between 410 and 440 and can be seen as a first hint for a settlement outside the fort (Haupt/Jung 2006, 47).

A fort similar to that in Alzey was built over the ruins of the *vicus Cruciniacum* in Bad Kreuznach around 369/370 (Haupt/Jung 2006, 49). The fort was probably used for the temporary stationing of units from the field army. Two combs with a bell-shaped handle dating to the first and second third of the 5<sup>th</sup> century were found within the fort area and are seen in an “East-Germanic” cultural context. The latest finds of wheel-decorated Argonne ware can be dated around the middle of the 5<sup>th</sup> century (440/450) (Bakker 2012, 69). The lack of ware with Christian symbols, which begins to appear in the region in the middle of the 5<sup>th</sup> century, was interpreted as an absence of purchasing power of a military community (Bakker 2012, 69). From the cemetery, which was continuously occupied from the Iron Age until the Early Middle Ages, a grave is known which contained a crossguard with rolled silver fittings and four red stone inlays that is also supposed to be of “East-Germanic” provenance (Bernhard 1982, 99–101; Bernhard 2007, 122–123).

The *vicus Bingium* in Bingen was fortified with new walls during the Valentinian period in the second half of the 4<sup>th</sup> century. This place was the residence of the *milites Bingenses* in the first half of the 5<sup>th</sup> century which are mentioned in the *Notitia Dignitatum* (Knöchlein 2003, 134–135). Even though the state of research is poor, based on grave finds it is assumed that Bingen was continuously settled from the Roman to the Early Medieval period (Knöchlein 2003, 159–220). Objects of “Germanic” origin are absent from the inventories of the late Roman graves, indicating that there was no infiltration of barbarian individuals or groups which contrasts to the situation at other places (Knöchlein 2003, 219; Haupt/Jung 2006, 48; Bernhard 2007, 123).

The Roman settlement (*vicus*) of Eisenberg was strongly destroyed during the barbarian raids of 352/353 but some buildings were renovated in the late 4<sup>th</sup> and early 5<sup>th</sup> century (Bernhard 2006, 136). Around 369/370, a special fortification (*burgus*) was built over the ruins in order to protect the road to inner Gaul (Bernhard 2006, 136). The investigation of ceramic vessels has shown that the building was still in use in the first half of the 5<sup>th</sup> century which coincides with the period 2 of Alzey (Bernhard 2006, 137). An “East-Germanic” element is possibly the comb with a

handle in a beaker form (Bernhard 2006, 137). The find of a bread stamp shows early Christian influences (Bernhard 2006, 137).

In the fortification of Ungstein, the ceramics from the infilling of a well are also mainly from the period 2 of Alzey. The well was filled with construction waste in the same way as in Alzey. Additionally, burn marks on the wall stones and ceramics may indicate the destruction of this building through fire (Bernhard 1981, 31–33; Bernhard 2006, 138). Several inhumation graves without grave goods found in the vicinity of the building were probably the inhabitants (Bernhard 1981, 34–45; Bernhard 2006, 139). The fortification fell into disuse around 430, suggested by the lack of a special ceramic in Alzey and the Burgundian narrative regarding its destruction in 436/443 (Bernhard 2006, 139).

The fort *Alta ripa* near Altrip at the mouth of the Neckar, which was also built under Valentinian around 369/370, ended with a fire catastrophe and was probably destroyed around 405/406/407 or 412. The latest wheel-decorated ware of this place dates around 435/430 (Bakker 2012, 7). After that date, the building was no longer in military use. The presence of two weaver huts of the 5<sup>th</sup> century shows that the area was probably still in use until the 8<sup>th</sup> century. An associated cemetery is not known (Bernhard 1997, 81–84).

### *1.2.2.3 Rural settlements and cemeteries in late Roman context*

The earliest early medieval cemeteries of the late 5<sup>th</sup> century were mainly founded in the rural areas of the western Upper Rhine Valley (see 1.2.2.4). Therefore, the rural settlements and cemeteries of the Late Roman period are of special importance in order to estimate continuity between the periods and to evaluate the possibility that late Roman settlers of the Upper Rhine Valley were involved in the creation of a new funeral rite in the second half of the 5<sup>th</sup> century. In the following, the late Roman finds of the 5<sup>th</sup> century in the rural areas of Mainz, Worms and Speyer will be presented.

In the rural area of the northern part of Rhine Hesse region, in the hinterland of Mainz, no cemeteries or Roman villas have been excavated recovering latest Roman finds. It seems that only the larger or fortified settlements such as Mainz, Bad Kreuznach, Bingen and Alzey were inhabited during the 5<sup>th</sup> century (Müller-Wille/Oldenstein 1981, 276–277; Blaich 2005, 51–52). However, the reason for the near absence of latest Roman finds may be due to the poor state of research and a lack

of excavations and datable objects rather than the depopulation of the area (Blaich 2005, 51). It is postulated that future research will demonstrate that there were intact rural settlements in the 5<sup>th</sup> century and that the inhabitants were mainly of “Germanic” origin (Bernhard 2007, 124). One of the few remains identified, which was probably one of the most important and precious burials of the first half of the 5<sup>th</sup> century in Central Europe, was found near Wolfsheim (Quast 2009, 376). In the 19<sup>th</sup> century, golden objects of an incomplete burial, which was destroyed by a plough, were found in the vicinity of three sarcophagi, indicating a late Roman cemetery and settlement. The objects include a golden pectoral with almandine inlays and a Persian inscription on the back, a golden neck ring, an amber pearl, a golden coin and fibula as well as golden buckles and an arm ring (Bernhard 1982, 82–85). The objects are seen in an “East-Germanic”-Danubian cultural context comparable to that of the Altlußheim grave 75 km away, which is one of few richly graves (*Prunkgräber*) on the grounds of the Western Roman Empire which date between 410 and 440 (Quast 2009, 374, Fig. 2). These objects may demark the burial of a Hunnic equestrian warrior, who was a soldier in a Roman auxiliary troop under Aëtius or a recruited “Germanic” soldier for the protection of the Roman border (Bernhard 2007, 124). This burial was also connected with the postulated Burgundian occupation of this region (Knöchlein/Rupprecht 1998, 226).

Even if the archaeological remains in the rural area in the hinterland of Worms were mainly from older excavations, the state of research in the southern part of the Rhine Hesse region and the northern part of the Palatinate region is better than in the northern part of the Rhine Hesse region. Several finds from Roman villas and associated cemeteries in this area have shown that Roman structures were still intact in the first half of the 5<sup>th</sup> century and likely in the second half of the 5<sup>th</sup> century as well (Bernhard 1981, 5; Bernhard 1997, 13, 16–32; Bernhard 2006, 167). As already mentioned, the small fortification in Eisenberg was in use until around 430/440. A civil settlement also existed which is indicated by the presence of the cemetery of Bems which belonged to a Roman villa, located around 2 km from the fortification. Several graves with rich grave goods were found which date to the first half of the 5<sup>th</sup> century. One of these graves can also be dated to the middle of the 5<sup>th</sup> century or later (Bernhard 1981, 75–84; Bernhard 1999, 32; Bernhard 2006, 138; Bernhard 2008a, 105). Several other graves belonging to Roman villas, many with rich grave goods in



the hinterland of Worms, are known from Asselheim, Obrigheim, Albisheim, Offstein, Einselthum, and Harxheim (Bernhard 1997, 32–54; Bernhard 2008a, 104). Some of the finds, such as weapons and few inhumation graves, are interpreted as verification of the presence of “Germanic” groups (Bernhard 1981, 78–79; Bernhard 1997, 34, 50; Bernhard 1999). A “Germanic” belt buckle from a putative grave found together with two jugs from Worms-Abenheim date to the first half or the middle of the 5<sup>th</sup> century and were also discussed in the context of the presence of Burgundians (Knöchlein/Rupprecht 1998, 226; Bernhard 1999, 226; Bernhard 1999, 41–42; Grünewald/Wieczorek 2012, 12). In Worms-Weinsheim, a well belonging to a Roman settlement was excavated which yielded finds for the time span around 430/440 (Bernhard 2008c, 155; 178).

There are some additional single finds, graves or smaller cemeteries which cannot be clearly assigned to a late Roman or early medieval context. For example, the smith grave from Nonnenhof in the vicinity of Bobenheim-Roxheim is unclear. A so-called crossbow brooch of the type Prague dates the grave in the middle of the 5<sup>th</sup> century. The 35 year old male individual with smith utensils is supposed to have emigrated from the middle Danubian region (Bernhard 1997, 98–100; Bernhard 2008b, 177–179, Tobias 2008, 181–182). As there is an early medieval cemetery in the vicinity of the smith grave, it cannot be excluded that it represents the founder grave of this burial place. However, such an early beginning of early medieval cemeteries is rather unusual. It may also be a single grave associated with a late Roman settlement or in the context of the military defence of the border (Bernhard 2008b, 177–179). Others interpret this grave as being connected to the time after the decline of the Roman administration in this area (Tobias 2008, 182–183; Grünewald/Wieczorek 2012, 12). Further examples already date to the second half of the 5<sup>th</sup> century. At the site of Monsheim III, only four graves were found (Grünewald/Koch 2009, 698). It is assumed that this may be a shortly occupied cemetery of the late 5<sup>th</sup> century which is typical for Alemannic sites, such as Lampertheim-Hofheim, on the eastern side of the Rhine (Grünewald/Koch 2009, 82). The findings show influences from “Elbe-Germanic”-Danubian cultural contexts such as two brooches of the SD-phase 1 (ca. 440–460) (Grünewald/Koch 2009, 698; Bernhard 2008b, 177). In Mettenheim, an “Elbe-Germanic”-Danubian chip-carved decorated bow brooch of the SD-phase 2 (ca. 460–480) was found. However, the

exact site is unknown and a connection with the early medieval cemetery, which dates to a time span beginning 20 years later, is not yet possible (Grünewald/Koch 2009, 82).

In the rural area in the hinterland of Speyer, numerous Roman villas were destroyed and abandoned during the 3<sup>rd</sup> and 4<sup>th</sup> centuries. However, several objects from late Roman graves and villas were found which prove the existence of Roman settlements until the middle of the 5<sup>th</sup> century. In the villa of Gommersheim, several coins were found which were still in use during the 5<sup>th</sup> century (Bernhard 2007, 120). A further example is the almost completely excavated villa of Wachenheim. After the building was destroyed around 352–369, a new group of likely non-Roman origin settled in the buildings. Archaeological remains include two pit houses in the direct vicinity of the villa, which were in use until the end of the 4<sup>th</sup> century probably around 400. Several finds, such as hand-made pottery of Alemannic tradition, a small iron shield grip as well as a bronze neck ring, point to the “Germanic” origin of these settlers. In some rooms of the building, an additional settlement horizon was found which dates to the time between 400 and 430 and ends with a fire. There are a few hints that after this destruction, parts of the building remained in use. A small cemetery is connected with this settlement period. The twelve graves are mainly without grave goods except one grave that yielded objects which are dated to the middle third of the 5<sup>th</sup> century. Burials without grave goods of the Late Roman period were generally assigned to “Romans”. However, it cannot be excluded that the interred individuals of the small cemetery are the descendants of the supposed “Germanic” settlers of the villa at the time around 400 (Bernhard 1997, 21–23). Indeed, several graves of the Late Roman period have been found, which were richly equipped with pottery and glass vessels and some imported objects. Some objects were found which are categorised in a “Germanic” tradition. These graves are known, for example, from Ruppertsberg and Gönheim (Bernhard 1997, 16–32; Bernhard 2007, 120).

#### *1.2.2.4 Rural settlements and cemeteries in an early medieval context*

At the end of the 5<sup>th</sup> century in the rural area of Rhine Hesse and Palatinate, several new cemeteries were founded that developed into the typical row-grave cemeteries which are known from a wide area in Western and Central Europe and were occupied

until around the middle of the 8<sup>th</sup> century. Most of the archaeological remains of the Early Medieval period are recovered from these cemeteries. Settlements are often difficult to find because they are buried under the modern villages. The few early settlements which are known from the western Upper Rhine Valley were found in Speyer, as discussed above. Even if the new cemeteries are often near late Roman settlements, in the rural areas of Rhine Hesse and Palatinate no cemeteries that were continuously in use from the Late Roman to the Early Medieval period have yet been identified. There is some uncertainty as to when the new settlements and cemeteries exactly started. While some authors assume that the area was already settled in the last third of the 5<sup>th</sup> century (Bernhard 1997, 104; Engels 2005a, 327; Engels 2012, 210–211), others suppose that it was just around 500 because there are only few finds which can be dated between before 500 (Koch 2008, 108; Grünewald/Koch 2009, 80). Finds from graves which are typical for the third quarter of the 5<sup>th</sup> century (SD-phase 2 = ca. 460–480) of newly founded cemeteries and were continuously occupied during Merovingian times are known from Mainz-Finthen (Engels 2008), Flomborn (Lange 2004), Obrigheim (Engels 2005b) and Eppstein (Engels 2012). The site of Mainz-Finthen in the north of Rhine Hesse is a relatively small but not completely excavated cemetery that yielded 50 graves with around 89 individuals and was in use probably until the late 7<sup>th</sup>/early 8<sup>th</sup> century (Engels 2008, 46). Engels dates the grave 35 of a male individual equipped with an axe, arrow heads and pottery “without sufficient safety” to the SD-phase 2 and interprets the grave in cultural proximity to the proto- and early Merovingian graves of Eschborn because of the reduced offering of weapons (Engels 2008, 13). Further early graves (graves 1 and 41) can be dated to the last third of the 5<sup>th</sup> century or rather around 500 (SD-phase 3 = ca. 480–510) (Engels 2008, 13; 48–54). The vessels of type B6d, which are adapted to Roman production but exhibit “Germanic” form traditions, are generally seen in a Rhine Frankish rather than in an Alemannic cultural context (Engels 2005a, 15; 37–38; Grünewald/Koch 2009, 82). Engels interprets this as a sign of continuity and doubts that larger immigrations took place in the late 5<sup>th</sup> and early 6<sup>th</sup> centuries (Engels 2008, 13; 39). The earliest finds from the cemetery of Flomborn are without connections to certain graves and date to the beginning (bronze bowl with grooved wall from grave 55), the middle (Pannonian *Nuppenbecher* of 1848) and the last third of the 5<sup>th</sup> century (find number 5 of 1888 and 1892; bow brooches of 1848) (Lange 2004, 237).

However, it is supposed that the findings are too meagre in order to expect a regular occupation already in the last third of the 5<sup>th</sup> century. The establishment of the cemetery in the years around 500 with burial 55 probably as the founder grave is considered to be more likely. Furthermore, it is excluded that these graves are a proof for the presence of Alemannic groups in the area (Lange 2004, 237). However, other researchers classify the findings of 1848 (Lange 2004, 26) in an “Elbe-Germanic”-Danubian context which are typical for Alemannic burial places east of the Rhine (Grünewald/Koch 2009, 82). The cemetery of Obrigheim was excavated in the 19<sup>th</sup> century. Most of the findings are without a specific grave context and the burial place is very poorly documented (Lange 2004, 7; Engels 2005a, 103). Objects which date to the third quarter of the 5<sup>th</sup> century are a special axe, a Sigilatta bowl as well as a chip-carved decorated triple knob brooch (Engels 2005a, 104–105). Furthermore, single finds, such as a comb with three layers, a Nigra vessel and possibly the remains of a bell beaker glass vessel, can also be dated to this early period (Engels 2005a, 104–105; Bernhard 2008c, 157). Somewhat older is a chip-carved, decorated belt fitting which was in a female grave in secondary use (Engels 2005a, Koch 2008, 108). In the modern and almost completely excavated cemetery of Eppstein, several graves date to the third quarter of the 5<sup>th</sup> century (Engels 2012, 198). As a result of the strong plundering of these early graves it is not possible to date them with safety to the SD-phase 2, as it is not possible to easily separate the graves of the SD-phases 2 and 3 (Grünewald/Koch 2009, 80; Engels 2012, 273). Engels interprets these early pre-Merovingian founder graves as “poly-ethnic” or “multi-cultural” because they show cultural influences from Roman (local), Alemannic (Southwest Germany) as well as “Elbe-Germanic”-Thuringian (Middle Germany) contexts (Engels 2012, 210–212). Additionally, single finds from the cemetery of Hechtsheim in Rhine Hesse can be dated to the SD-phase 2 (Koch 2013, 123). However, as these finds only belong to two individuals it is not supposed that the settlement and the establishment of the cemetery already ensued in the 5<sup>th</sup> century (Koch 2013, 123). As the number of graves and finds of the mentioned cemeteries with finds of the SD-phase 2 are also very low, a later foundation only around 500 could also apply to these sites. However, as a result of the poor state of research the opposite could also be accurate.

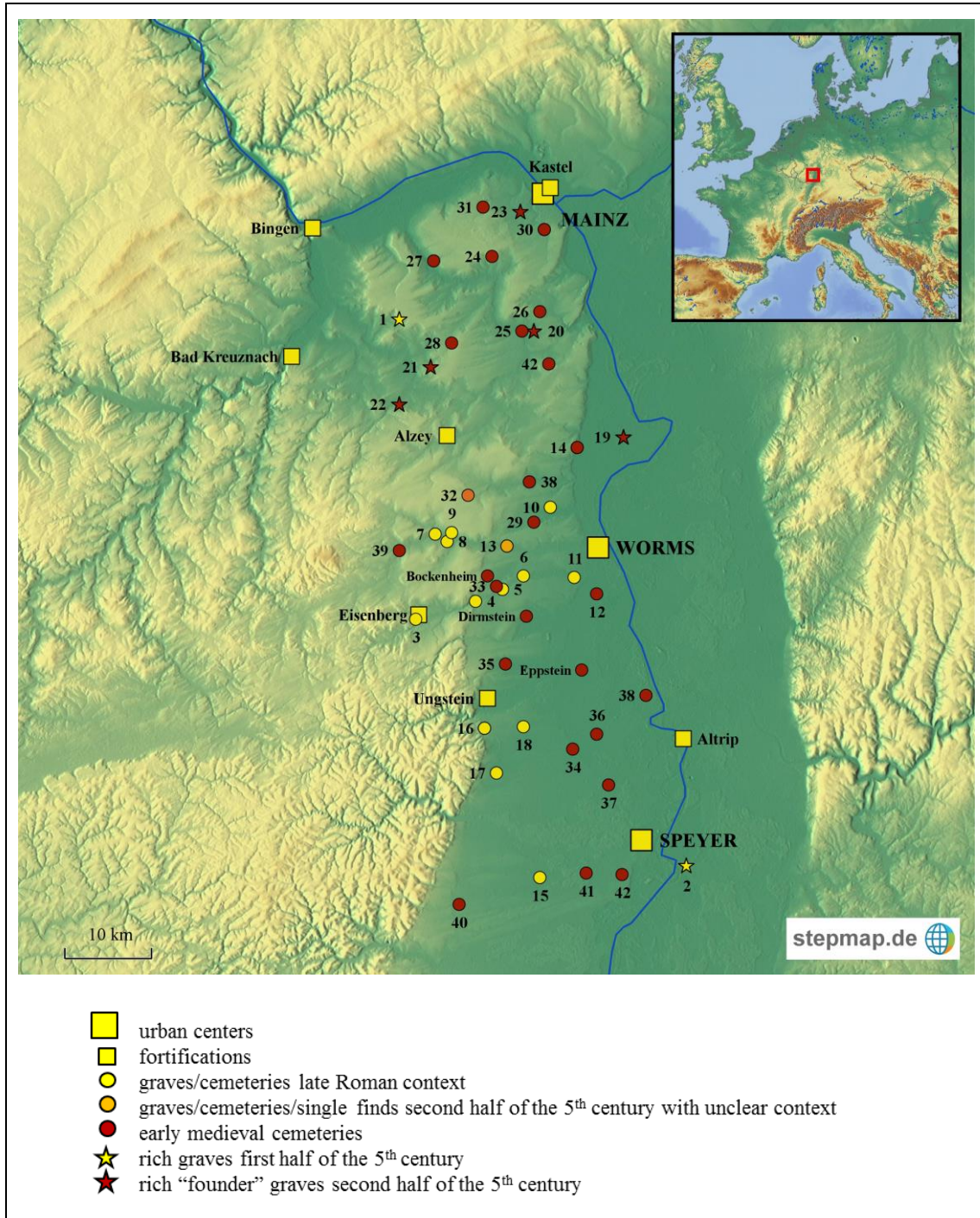
In the decades around 500 (SD-phase 3 = ca. 480–510), there are more indications of settlement in the area. In the Rhine Hesse region, several cemeteries are

known which yielded graves of the SD-phase 3 (Zeller 1992; Müller-Wille/Oldenstein 1981; Blaich 2005; Grünewald/Koch 2009). Most of the cemeteries examined during older excavations were not completely excavated and have not yet been investigated with modern techniques. However, a peculiarity is worth mentioning. Several cemeteries were found which revealed rich founder graves of the so-called “Flonheim-Gültlingen-horizon”, observed most famously in the burial of Childeric in Tournai (Ament 1970; Müller-Wille/Oldenstein 1981, 277; Blaich 2005, 53). In Rhine Hesse, these include a rider grave with a horse from Selzen (Zeller 1992, 194–196), a grave with a preciously decorated sword (*Prunkschwert*) from Rommersheim as well as from Eich (Wieczorek 1996, 895–898; Grünewald/Koch 2009, 506–518), Flonheim (Ament 1970, 127–129) and Bretzenheim (Wunsch 2006). It is striking that these graves are situated in the vicinity of former military fortifications and at strategically important routes. The traditional interpretation of these graves is that the interred humans represent followers or “*Funktionsträger*” of Clovis, who had granted lands to them in conquered territory where they subsequently settled. However, it is not clearly attested when the Upper Rhine Valley was conquered by Clovis. The date is mainly equated with the battle against the Alemanns in 496/497 (Ament 1970, 164), but they were not finally defeated by the Franks until 506. An alternative explanation is that local families might have sided with the Franks and adopted their identity in order to demonstrate prestige and power during that unstable political period (Halsall 2009; Theuvs 2009). Further continuously occupied cemeteries which were established at the same time as the “elite” graves are known from Ober-Olm, Hahnheim, Mommenheim, Schwabenheim und Wörrstadt (Müller-Wille/Oldenstein 1981, 277–278; Blaich 2005, 53) as well as at Mörrstadt and as already mentioned at Hechtsheim (Grünewald/Koch 2009, 790; Koch 2013).

In the Palatinate region, continuously occupied cemeteries first created around 500 are known from Bockenheim (Bernhard 1997, 39–42; Riemer 2008, 151–154) and Dannstadt-Bierkrautgewanne (Bernhard 1997, 57–59). From the cemetery of Freinsheim, only the find of a single ceramic vessel indicates its foundation at the end of the 5<sup>th</sup> century (Bernhard 1997, 59). This is also the case for Mutterstadt and Schifferstadt (Bernhard 1997, 70). In Ludwigshafen, two superimposed burials were found in the area of Gartenstadt-Hochfeld. The burial contained a bell beaker, dating the grave to the 5<sup>th</sup> century. It is unclear if this is a single grave or part of a larger

burial place which has not yet been found (Polenz 1988, 257–258). The western border of this early “settlement wave” is found at the cemetery of Marnheim. One of the graves can be dated to the time before 500, but this does not indicate a simultaneous settlement inception. The most southern places of this time are Edesheim (Bernhard 1997, 70–74) and Römerberg-Heiligenstein (Bernhard 1997, 81) whose oldest graves date around 500. To the south of these sites as well as on the eastern side of the Rhine, the foundation of new settlements and cemeteries starts 1–2 generations later (Bernhard 1997, 81; Koch/Koch 1996; Koch 2000, 58–59; Koch 2007).

Most of the known cemeteries date to the beginning of the 6<sup>th</sup> century during the SD-phases 4 and 5 between ca. 510–555 (Grünwald/Koch 2009, 80–84). Almost each modern village in the Upper Rhine Valley has at least one cemetery dating to this period. Even if the increase in identified cemeteries is influenced by the state of research, it is conspicuous that numerous cemeteries are associated with the first half of the 6<sup>th</sup> century. However, none of these cemeteries have been completely excavated and it has not yet been determined whether all settlements were established simultaneously or over a longer time period (Grünwald/Koch 2009, 84). As this is a time of the reign of the Merovingians in the Upper Rhine Valley, it is assumed that settlement took place as an administrated process and mainly with the help of new settlers. It is supposed that the Merovingian kings rewarded soldiers and officers of the Frankish army with land grants (Koch 2000; Grünwald/Koch 2009, 84). In a few cemeteries it was observed that new settlers started to bury their dead on already existing cemeteries. This was the case in Mörstadt, Dirmstein and Westhofen (Grünwald/Koch 2009, 84; Wiczorek et al. 2009; Leithäuser 2011). Certain elements of the costume and grave goods, especially hand-made pottery, horse burials, north-south orientated graves etc., are seen as evidence for the immigration of individuals and groups from the North Sea area and Middle Germany (Wiczorek 1989; Wiczorek et al. 1996; Gross 1999; Koch 2000; Stauch 2004; Koch 2007; Leithäuser 2011; Engels 2012; Koch 2012a). Fig. 1.1 provides an overview of the location of the sites which are mentioned in the text.



**Fig. 1.1. Sites of the 5<sup>th</sup> and early 6<sup>th</sup> centuries on the western bank of the northern Upper Rhine Valley which are mentioned in the text.**

1. Wolfsheim; 2. Altlußheim; 3. Eisenberg; 4. Asselheim; 5. Obrigheim; 6. Offstein; 7. Albisheim; 8. Harxheim; 9. Einselfthum; 10. Abenheim; 11. Weinsheim; 12. Bobenheim-Roxheim; 13. Monsheim; 14. Mettenheim; 15. Gommersheim; 16. Wachenheim; 17. Ruppertsberg; 18. Gönheim; 19. Eich; 20. Selzen; 21. Rommersheim; 22. Flonheim; 23. Bretzenheim; 24. Ober-Olm; 25. Hahnheim; 26. Mommenheim; 27. Schwabenheim; 28. Wörrstadt; 29. Mörstadt; 30. Hechtsheim; 31. Finthen; 32. Flornborn; 33. Obrigheim; 34. Dannstadt; 35. Freinsheim; 36. Mutterstadt; 37. Schifferstadt; 38. Ludwigshafen; 39. Marnheim; 40. Edesheim; 41. Römerberg; 42. Westhofen

### 1.3 Summary

In the following, the main developments of the 5<sup>th</sup> and the early 6<sup>th</sup> century in the Upper Rhine Valley, which can be deduced from the written and archaeological records, will be summarised (as stated in more detail in the preceding chapters 1.1 and 1.2). Furthermore, their connections to socio-political events will be subsequently outlined.

It is assumed that the urban centres in the northern Upper Rhine Valley, Mainz, Worms and Speyer, were continuously settled during the 5<sup>th</sup> and 6<sup>th</sup> centuries. However, in all three towns, there are only few graves and single finds from the Roman cemeteries and the areas within the town walls which can be dated to the Late Roman period in the first half of the 5<sup>th</sup> century (Bernhard 2007, 118–119; Knöchlein 2011, 276–282; Grünewald/Wieczorek 2012, 12–14). This is probably the result of the reduced or absent deposition of grave offerings, the lack of good datable objects and the general poor state of research. Nevertheless, in combination with the written sources and the small quantity of archaeological evidence it can be assumed that there was an intact military and civil settlement under Roman administration until the middle of the 5<sup>th</sup> century. Some of the few datable objects are of “Germanic” origin and indicate the presence of non-Roman military and civil persons (Bernhard 1982; Bernhard 1999; Bernhard 2007). In Worms and Speyer, no archaeological indications of a destruction horizon were found which can be connected to the events which were described in the written sources such as the “invasions” at the beginning of the 5<sup>th</sup> century, the Burgundian occupation since 412 and their forceful displacement around 435/443 or the Hunnic invasion in 451 (Bernhard 2007, 119; Grünewald/Wieczorek 2012, 12). In Mainz, two treasure troves are seen in the context of the crossing of the Rhine by barbarian groups around 405/406/407 and at the beginning of the Burgundian occupation around 411 (Knöchlein 2011, 276). Finds from the time between the cessation of Roman influence around 450 and the beginning of Merovingian influence at the beginning of the 6<sup>th</sup> century are almost absent in Mainz and Worms (Knöchlein 2011, 276–282; Grünewald/Wieczorek 2012, 12–14). In Speyer, which was only partly destroyed during the Second World War, the state of research is much better. Around 700 graves mainly without grave offerings assumedly date between 400 and 480. Furthermore, remains of buildings were found which



prove the existence of an intact settlement structure after the middle of the 5<sup>th</sup> century until around 460/470 (Bernhard 2007, 118–119). Moreover, another settlement from an early medieval context already dates to the end of the 5<sup>th</sup> century and is connected to the immigration of newcomers from the North Sea area (Bernhard 1997, 95). In all three towns, the known row-grave cemeteries of the Merovingian period only commenced during the 6<sup>th</sup> century and are situated at the fringes of the Roman cemeteries outside the town wall (Bernhard 2007, 118–119; Knöchlein 2011, 276–282; Grünewald/Wieczorek 2012, 12–14). Based on the poor state of research, it is assumed but it cannot be stated with certainty if the cemeteries were continuously settled from the Roman to the Early Medieval period.

Archaeological investigations have shown that most of the fortifications in the northern Upper Rhine Valley, which were built around 369/370 under Valentinian I, were in military use until the middle of the 5<sup>th</sup> century (440/450) (Oldenstein 1992; Bakker 2012, 69). Some of them, such as the fort in Altrip or the *burgi* in Eisenberg and Ungstein, probably ended already around 425/430/440 (Bernhard 2006, 136–137; Bakker 2012, 7). To what extent the end of the military use of these stations and the detected destruction horizons can be connected to historical events of the first half of the 5<sup>th</sup> century remains only speculation. However, from all sites, with the exception of Bingen, finds of “East-Germanic” cultural provenance were found which indicate the presence of non-Roman soldiers (Bernhard 1982, 99–101; Bernhard 2006, 137; Bernhard 2007, 122–123). Even if finds dating to the second half of the 5<sup>th</sup> century are almost absent, it is assumed that the fortifications were used by civil communities after military influence had disappeared (Gupte/Haupt, 153).

More appropriate for evaluation – if there was continuity between the Late Roman and the Early Medieval period – are the rural settlements and cemeteries in the Rhine Hesse and Palatinate regions. In the northernmost area of the Upper Rhine Valley in the region around Mainz, there are, except for the rich grave of Wolfsheim with objects of “East-Germanic” influence, no findings which prove the continuity of Roman settlements in the first half of the 5<sup>th</sup> century. This is likely due to the poor state of research (Müller-Wille/Oldenstein 1981, 276–277; Blaich 2005, 51–52). However, further south in the rural areas around Worms and Speyer several finds prove the existence of Roman structures until the middle of the 5<sup>th</sup> century (Bernhard 1982, 5; Bernhard 1997, 13–32; Bernhard 2006, 167). The presence of graves with

rich graves goods, imported objects as well as expensive sarcophagi clearly shows that wealthy communities had settled in the area (Bernhard 1997, 16–32; Bernhard 2007, 120). Furthermore, graves with objects of non-Roman origin were interpreted as remains of “Germanic” settlers (Bernhard 1981, 78–79; Bernhard 1997, 34; 50; Bernhard 1999). Single graves from these late Roman cemeteries can also be dated to the second half of the 5<sup>th</sup> century. These latest Roman graves and other single graves, which cannot be assigned clearly to a late Roman or an early medieval context, close the gap to the earliest early medieval cemeteries which tentatively start in the last third of the 5<sup>th</sup> century (Bernhard 1997, 104; Engels 2005a, 327; Engels 2012, 210–211). This indicates that not only newcomers but also local communities might have been involved in the establishment of a new burial rite at the beginning of the Early Medieval period in the northern Upper Rhine Valley. To what extent these cultural influences reflect “Alemannic”, “Rhine Frankish” or “Roman” groups remains a matter of speculation. Based on the archaeological record of the 5<sup>th</sup> century, it can principally be stated that already during the first half of the 5<sup>th</sup> and increasingly during the second half of the 5<sup>th</sup> century different cultural influences are detectable which indicate a heterogeneous demographic structure, probably as a main result of the immigration of newcomers. In addition, the location of the Upper Rhine Valley in a border area and as a cultural contact zone already opened the region to diverse cultural influences during the Late Roman period but also increasingly after Roman structures had finally ceased.

While the population density was still relatively low in the second half of the 5<sup>th</sup> century, there was a rapid increase at the beginning of and during the 6<sup>th</sup> century, visible in the establishment of several row-grave cemeteries (Grünwald/Koch 2009, 80–84). At that time, the region was under the influence of the Frankish kings of the Merovingian dynasty. Several grave goods, especially hand-made vessels which are typical for other areas, make it probable that the settlement of groups from the North Sea area, Middle Germany as well as from Southwest Germany was an administrated process in the name of the Merovingian kings (Koch 2000; Grünwald/Koch 2009, 80–84; Leithäuser 2011, 224; Engels 2012, 200–201).

### *Connection to the overall socio-political changes*

The described structural changes in the Upper Rhine Valley can be connected to the overall socio-political processes of the 5<sup>th</sup> and 6<sup>th</sup> centuries. The first half of the 5<sup>th</sup>

century is characterised by increased geographic mobility. As a result of the decentralisation of the Roman administration, non-Roman groups increasingly began to invade the Western Roman Empire. The Roman army was more and more dependent on non-Roman federates to protect the border and was forced to legalise the settlement of military confederations which had previously conquered areas on the western side of the Rhine, which included the Rhenish Franks in the Lower Rhine area around Cologne, the Salian Franks in Belgium and Northern France and the Burgundians in a region near the Rhine. Whether the Burgundians settled at the Upper Rhine Valley in the region around Worms is not provable. However, based on objects of supposed “Germanic” origin, which were found in the urban centres, military fortifications and also in rural settlements and cemeteries, the presence of non-Roman military and civil persons can be assumed. Furthermore, in contrast to the general reduced or absent placing of grave goods in late Roman cemeteries, in the rural areas of the Palatinate region, several richly equipped graves have been detected which prove the existence of wealthy communities during the first half of the 5<sup>th</sup> century in the Upper Rhine Valley. The archaeological evidences make it probable that there was a heterogeneous demographic structure with individuals of diverse backgrounds already during the 5<sup>th</sup> century.

The second half of the 5<sup>th</sup> century was the beginning of the gradual dissolution of Roman influence which finally ceased with the removal of the last Western Roman emperors in 476 and 480. The disintegration of Roman power was followed by dynamic processes which resulted in a struggle for power between Roman military commanders, non-Roman rulers, such as the kings of the Visigoths and Burgundians, and also high military persons of Frankish origin. Moreover, Alemannic and Frankish groups from the right side of the Rhine started raids and expeditions of conquests into areas on the left side of the Rhine. The written and archaeological records indicate that the Roman military impact on the Upper Rhine Valley already started to disband around the middle of the 5<sup>th</sup> century. The last attested inspection of the Rhine border by a Roman military commander took place in the year 455. Furthermore, Roman fortifications were no longer in military use by the middle of the 5<sup>th</sup> century. However, even if the current state of research is still poor, it can be stated that the Upper Rhine Valley was not completely depopulated after the Roman military structures had dissolved. Actually, it has been shown that single graves of late Roman

cemeteries which are connected to Roman villas in the rural area of the Palatinate region date to the second half of the 5<sup>th</sup> century. In addition, other graves and single finds were found which date after 450 but cannot be assigned clearly to a late Roman or early medieval context. As the earliest freshly founded early medieval cemeteries already date the SD-phase 2 (ca. 460–480), it is likely that there was an overlap of Roman structures in the form of Roman villas and the first early medieval cemeteries. Furthermore, in the urban centre of Speyer, civil buildings were recovered which can be dated to 460/70 and one of the few excavated early medieval settlements known from Speyer already dates to the end of the 5<sup>th</sup> century. To what extent these remains reflect Alemannic groups, Rhenish Franks and former members of federate “Germanic” soldiers, who had served in the Roman army, remains disputed. However, based on the archaeological record it is likely that people of different origin, including local communities, were present in the Upper Rhine Valley during the second half of the 5<sup>th</sup> century and established the new burial rite as a result of the unstable socio-political situation.

At the beginning of the 6<sup>th</sup> century, the Upper Rhine Valley was under the sovereignty of the Merovingians. Clovis, who probably succeeded his father Childeric as ruler of the Salian Franks and administrator of the Belgica II in 481/82, has conquered an area extending from the Rhine in the northeast to the Garonne in the southwest at the beginning of the 6<sup>th</sup> century. He defeated the last “Gallo-Roman” military leader in Northern Gaul in 486/487, the Alemanns finally in 506 and also eliminated his relatives and other Salian and Rhenish kings in order to establish his autocracy. In 511, when Clovis died, the Upper Rhine Valley fell into the hands of his eldest son Theuderic. In the 530s, Theuderic and his relatives defeated the Burgundian and the Thuringian kingdoms and extended the Merovingian kingdom further to the southwest and southeast. In 533, Theuderic died and the Upper Rhine Valley was inherited by his son Theudebert, who was successful in the conquest of southern Aquitaine as well as in the consolidation of his position in the 540s in Rhaetia, the Noric provinces and in parts of Northern Italy. No written sources are known which report on the situation in the Upper Rhine Valley in more detail. However, based on the archaeological record it is known that already in the years around 500 during the SD-phase 3 (ca. 480–510), several new cemeteries were founded in a limited area in the regions between Mainz and Speyer. Some of these freshly established cemeteries

yield rich founder graves of the so-called “Flonheim-Gültlingen-horizon”. These graves are traditionally interpreted as belonging to the followers of Clovis. However, as the dating of the conquest of the Upper Rhine Valley by Clovis and the possible time frame of the foundation of the graves (roughly between 480 and 510) are uncertain, it might also be the case that these graves represent a new form of self-display of local communities during times of crisis. In the following years, at the beginning of the 6<sup>th</sup> century, the region and adjacent areas were under the sovereignty of the Franks. Several new cemeteries were initiated at this time. This was connected to demographic growth in the region, which can only be explained by the immigration of newcomers as indicated by foreign material objects, especially hand-made pottery. It is conceivable that these settlements took place as an administrated process of the Merovingian king, who rewarded soldiers and officers of the Frankish army with land grants.

## 2 Methodological and biogeochemical background

### 2.1 Teeth as analytical materials for isotopic studies of mobility

Isotope analyses for the investigation of human mobility can be performed on a variety of tissues such as body fluids, soft tissues, nails, hair, bones and teeth. In archaeological studies most often only the hard skeletal tissues, such as bone and teeth, are available. During an individual's lifetime, specific element and isotope signatures are ingested via food and drink and after passing metabolic processes they are incorporated into hard tissues. The signatures are specific and depend on locality, season and diet. As a result of differences in the structure and composition of bone and teeth, the latter are more often and especially better preserved in the archaeological record. Therefore, tooth enamel is the tissue of choice for the investigation of mobility by means of strontium, oxygen and carbon isotope analyses. In the following, the most important aspects of dental enamel as an analyte for isotope investigations are outlined. For the sake of simplicity, the different teeth of the deciduous and permanent dentition are labelled in terms of a shorthand system which uses a combination of letters and numbers (see Tab. 2.1).

**Tab. 2.1. Shorthand systems for dentition (from Montgomery 2002, 48).**

Tooth name	Abbreviation				
	Deciduous Dentition		Permanent Dentition		Left or Right
	Maxillary	Mandibular	Maxillary	Mandibular	
First incisor	di <sup>1</sup>	di <sub>1</sub>	I <sup>1</sup>	I <sub>1</sub>	L or R
Second incisor	di <sup>2</sup>	di <sub>2</sub>	I <sup>2</sup>	I <sub>2</sub>	“
Canine	dc <sup>1</sup>	dc <sub>1</sub>	C <sup>1</sup>	C <sub>1</sub>	“
First premolar	-	-	P <sup>1</sup>	P <sub>1</sub>	“
Second premolar	-	-	P <sup>2</sup>	P <sub>2</sub>	“
First molar	dm <sup>1</sup>	dm <sub>1</sub>	M <sup>1</sup>	M <sub>1</sub>	“
Second molar	dm <sup>2</sup>	dm <sub>2</sub>	M <sup>2</sup>	M <sub>2</sub>	“
Third molar	-	-	M <sup>3</sup>	M <sub>3</sub>	“

#### 2.1.1 Structure and composition

Each human tooth consists of a crown and one or several roots. These parts are joined at the enamel-dentine junction (EDJ) that is the neck or cervix of the tooth. Dentine is

the tissue that forms the greatest part of the tooth, namely the crown and the roots. It also encompasses the dental pulp which contains blood vessels and nerves. The crown dentine is covered by 1–2 mm thick layer of enamel, while cementum covers the dentine outside of the root (Buddecke 1981, 2; Schumacher 1990, 13–16; Hillson 1996, 8; 148). Enamel, dentine and bones are composed of inorganic, organic and water fractions in varying amounts (Montgomery 2002, 56). The literature offers different information about the amount of the components of bones and teeth. The discrepancies may arise from variations between and within teeth and/or analytical difficulties (Montgomery 2002, 59–60). Mature enamel is the hardest and almost entirely mineralised skeletal tissue. More than 95% by weight of mature enamel is composed of mineralised material, while dentine contains around 70–80% and bone around 70% by dry weight of inorganic substances (Hillson 1996, 218, Tab. 10.1). The main part of the mineralised fraction of all three tissues is composed of biological or biogenic apatite, an impure crystalline calcium phosphate that resembles the composition of the mineralogical calcium phosphate hydroxyapatite or dahllite, idealised as  $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$ . In comparison to mineralogical apatite, biogenic apatite – which is mainly built of calcium (32–39%) and phosphate (16–18%) – additionally contains different compounds such as carbonate and fluorine as well as numerous trace elements such as magnesium, lead, strontium etc. which substitute for calcium (LeGeros 1981; Montgomery 2002, 56–57; Knipper 2011, 130). The apatite crystals of dental enamel build regularly formed, tightly packed prisms that are parallel to each other and cross the enamel radial from the EDJ to the surface (Knipper 2011, 130). The highly mineralised mature enamel is not only harder than dentine and bone but has also larger apatite crystals and is therefore less porous. Mature enamel contains between 0.2 and 0.6% organic substances, such as the proteins amelogenins and enamelin, but no collagen. In comparison, bone and dentine are comprised of around 20% organic material by dry weight which is mainly comprised of the protein collagen but also non-collagenous proteins (Hillson 1996, 218, Tab. 10.1; Montgomery 2002, 58–59; Knipper 2004, 603). While bones contain living cells and can be remodelled or renewed throughout life with a turnover rate depending on the type of bone, enamel contains no living cells, blood supply or nerves. Once formed and mineralised, tooth enamel can neither regenerate nor remodel and the enamel mineralised during childhood remains unchanged throughout life. Dentine is a living,

cellular tissue, but has no blood supply and is not subject to continual remodelling. Therefore, the composition of primary dentine is mainly determined at the time of formation. As the cells of dentine remain active, the formation of secondary dentine continues throughout life but probably not until the third decade of life. Secondary and irregular secondary dentine that are influenced by specific pressure, attrition or caries are mainly deposited in the pulp cavity (Buddecke 1981, 7; Montgomery 2002, 57–58; Knipper 2004, 601; Knipper 2011, 130–131).

### **2.1.2 Mineralisation and formation**

Elemental and isotopic signatures are only incorporated in the phase of enamel mineralisation of a particular tooth. The timing and duration of the formation and maturation of enamel is complex and still poorly understood (Montgomery/Evans 2006, 126). The dental development tables, which are used for the estimation of enamel mineralisation times, reflect, strictly speaking, only the time of tooth crown formation which is not identical to the more constrained time of tooth crown mineralisation. Even if a tooth crown is morphologically completely formed that does not indicate that it is fully mineralised (Montgomery 2002, 49; 53–56; Montgomery/Evans 2006, 126–127). The biomineralisation (amelogenesis) of tooth enamel is characterised as a transformation of an organic gel into mineral within several distinct phases (Simmer/Fincham 1995; Fincham et al. 1999; Montgomery 2002, 62). In short, the initial phases include the secretion of proteins, followed by the formation of crystallites which extend and are deposited in a sequential manner. In these first stages, the structural features of enamel are laid out but the fine crystallites which grow from the EDJ to the tooth surface represent only around 10% of the final enamel weight. The majority of mineralisation takes place in later phases during maturation where proteins are removed and the crystals expand laterally due to an influx of mineral ions which results in densely mineralised mature enamel with an inorganic component of around 96% (Hillson 1996; Fincham et al. 1999; Montgomery 2002; Bentley 2006, 172; Montgomery/Evans 2006, 126). Human enamel does not mineralise progressively from the cusp tip to the cervix and there is also no simple relationship between the incorporated minerals and incremental enamel structures (Montgomery/Evans 2006, 127). While it is supposed that the initial



formation of crystals reflect rather short-termed, maybe daily, incremental growth, the mineralisation during maturation occurs in multiple directions with different mineralisation fronts and a time span of several years depending on tooth type (Montgomery 2002, 68–70; Montgomery/Evans 2006, 126–127). Therefore, for human tooth enamel it is recommended to take bulk samples rather than to carry out micro-sampling (Montgomery/Evans 2006, 127; Wright 2013). In order to assess temporal changes in mobility, it is more useful to analysis multiple teeth from a single individual which allows an evaluation of changing isotopic patterns throughout childhood.

The formation of tooth crowns of human deciduous dentition starts in utero between the 4<sup>th</sup> and 6<sup>th</sup> month after fertilisation and is finished between the second and third month after birth for di1 followed by dm1, di2 as well as dc and dm2, which are complete in the last quarter of the first year of life (Hillson 1996, 121; Montgomery 2002, 50–51; Knipper 2011, 131–133). The initiation period of permanent tooth crowns starts also peri-natal with M1, followed by I1, I<sub>2</sub>, C1, I<sup>2</sup>, P1, P2, M2 and finally M3. The crown of the latter is complete with the highest individual variability predominantly during adolescent years (Montgomery 2002, 51–52; Knipper 2011, 133–134, Fig. 8.3, 132). It has to be noted that even if other authors have slightly different ranges for tooth crown formation or enamel mineralisation, there are only slight differences between different human groups and sexes (Tütken 2010, 35) with the exception of the M3 (Knipper 2011, 133–134).

## **2.2 Stable and radiogenic isotopes**

The majority of chemical elements exist in different atomic versions which are called isotopes. Isotopes of a given element are atoms whose nuclei have the same number of protons and electrons but a different number of neutrons. Most elements have stable and unstable isotopes. Unstable isotopes are commonly known as radioactive isotopes and undergo decay resulting in the emission of subatomic particles at a specific rate. Stable isotopes are energetically stable and consequently do not experience measureable decay. However, stable isotopes can be the product of the decay of radioactive isotopes and are called radiogenic isotopes. In nature, stable isotopes of elements are present as mixtures but in different amounts. The lightest

isotope is usually the most abundant species while the heavier isotope(s) are usually only present in trace amounts (Kendall/Caldwell 1998, 51–56; Hoefs 2009, 1–3). Due to variations in the atomic mass, isotopic atoms and molecules have slightly different physicochemical properties (isotope effect). As a result, the relative abundance of isotopes in a source compound and the product of a dynamic process are different. Every process in which changes in isotopic abundances occur is called fractionation (Mook 2000, 23–25; Hoefs 2009, 4–5). Based on the process which is responsible for the change, there are two main mass-dependent effects which produce isotope fractionations: equilibrium and kinetic fractionation. Equilibrium (also called thermodynamic or exchange) fractionation is the partial exchange of isotopes between substances or phases that are in equilibrium with each other. Equilibrium means that the amount and concentration of the chemical compounds involved do not change. The extent of the exchange is temperature dependent with the largest exchange occurring at the lowest temperature (Mook 2000, 25–27; Hoefs 2009, 6–10). Kinetic fractionations are incomplete or unidirectional processes (e.g. evaporation) and are associated with effects occurring from the breaking and making of chemical bonds and bio-chemical reactions and result in the accumulation of the lighter isotope in the product, depending on temperature (Mook 2000, 27–30; Hoefs 2009, 11). A special case of fractionation is transport fractionation which occurs due to different mobilities of the isotopic species of water. This effect is different from kinetic fractionation because the mass difference between the isotopic molecules is important, rather than the atomic mass difference (Gat et al. 2001, 178).

Isotope ratios are normally measured by isotope ratio mass spectrometry (IRMS). This method separates atoms or molecules on the basis of their mass to charge ratio (Faure/Mensing 2005, 64; Sharp 2007, 31–32; Hoefs 2009, 23–24). The IRMS is configured for analysis either for the lighter or heavier elements. Prior to isotope analysis, samples such as skeletal materials have to be pre-processed in the laboratory. Depending on the type of ion source, gaseous, solid or liquid samples can be analysed. For the measurement of light elements such as oxygen and carbon, there are commonly two configurations used, these are either continuous flow IRMS (CF-IRMS) or dual-inlet IRMS (DI-IRMS) (Sulzman 2007, 11–14). Depending on the material to be analysed (e.g. carbonates, water) and configuration, the precision ranges between  $\pm 0.1$  and  $0.04\%$ . Isotopes of heavy elements, such as strontium, are

commonly measured by thermal ionization mass spectrometry (TIMS), multicollector inductively coupled plasma mass spectrometry (MC-ICP-MS) analysis or currently also by laser ablation MC-ICPMS (Balter et al. 2008; Horstwood et al. 2008). With TIMS and MC-ICP-MS it is possible to measure, for example, strontium isotope ratios with an internal precision of  $\pm 0.0000010$  and an external precision of around  $\pm 0.000020$  ( $2\sigma$ ) (Slovak/Paytan 2012, 754). Instead of using the absolute isotope ratio, the composition of light elements such as oxygen and carbon are normally expressed in terms of their relative abundances using the delta-( $\delta$ ) notation system (McKinney et al. 1950; Sharp 2007, 27). Delta values are reported in parts per thousand (‰) relative to an internationally accepted standard of known composition (Hoefs 2009, 27, Tab. 1.6). Delta values are calculated by the following formula:

$$\delta (\text{‰}) = [(R_{\text{sample}}/R_{\text{standard}}) - 1] \times 1000$$

where R denotes the measured isotope ratio of the heavy to the light isotope, and  $R_{\text{sample}}$  and  $R_{\text{standard}}$  are the ratios in the sample and standard, respectively. A positive  $\delta$  value indicates that the sample has more of the heavy isotope than the standard does, while a negative  $\delta$  value indicates that the sample has less of the heavy isotope than the standard (Sharp 2007, 17; Hoefs 2009, 28). For heavy elements such as strontium, the  $\delta$ -notation system is only rarely used. More often it is common just to report the absolute ratio of measured isotope abundances (Koch 2007, 118).

### **2.2.1 Strontium isotope analysis**

The application of strontium isotope analysis of human tooth enamel for the investigation of past mobility is based on the assumption that regions with different bedrock geology tend to have distinct strontium isotopic signatures. These geochemical fingerprints are transmitted without relevant fractionation from bedrock to soil, water, plants and animals and finally into the human body. By comparing the local biologically available strontium signature of a region with the strontium signature of human dental enamel, it can be determined if a person obtained food and drink from this area during tissue mineralisation. This, in turn, permits the identification of local and non-locals and, hence, inferences about lifetime movements (Ericson 1985; Price et al. 2002a; Knipper 2004; Bentley 2006; Montgomery 2010).

### *2.2.1.1 Radiogenic strontium isotopes*

Strontium is a lithophilic alkaline earth element with a geochemical behaviour similar to calcium. It is one of the most abundant trace elements in rocks and surficial deposits and also available in different concentrations in several other materials such as water, soil, plants, animals and humans as well as atmospheric deposits (Capo et al. 1998, 198–201; 200, Tab. 1; Faure/Mensing 2005, 75; Slovak/Paytan 2012, 743). Strontium has four naturally occurring stable isotopes, including  $^{88}\text{Sr}$ ,  $^{87}\text{Sr}$ ,  $^{86}\text{Sr}$ , and  $^{84}\text{Sr}$  with abundances of ca. 82.53%, 7.04%, 9.87% and 0.56%, respectively. Whereas the amounts of  $^{88}\text{Sr}$ ,  $^{86}\text{Sr}$ , and  $^{84}\text{Sr}$  are constant over time, a fraction of  $^{87}\text{Sr}$  varies. This radiogenic  $^{87}\text{Sr}$  is derived from the radioactive decay of  $^{87}\text{Rb}$  with a half-life of approximately  $4.88 \times 10^{10}$  years. Therefore, the amount of  $^{87}\text{Sr}$  in a rock or mineral that contains Rb depends on the age of the parent material and the initial Rb/Sr ratio at the formation of that rock or mineral (Faure/Mensing 2005, 75–78). The amount of  $^{87}\text{Sr}$  changes so slow, that it is only relevant on a geological time scale but negligible on an archaeological time scale (Knipper 2004, 596–597). Commonly,  $^{87}\text{Sr}$  is measured against the constant  $^{86}\text{Sr}$  which has a similar abundance and atomic mass, and is expressed as  $^{87}\text{Sr}/^{86}\text{Sr}$ . In order to distinguish between mobility studies using  $^{87}\text{Sr}/^{86}\text{Sr}$  and recent diet studies using  $\delta^{88/86}\text{Sr}$ , it is recommended to use “radiogenic strontium isotopes” for  $^{87}\text{Sr}/^{86}\text{Sr}$  and “stable strontium isotopes” for  $\delta^{88/86}\text{Sr}$  (Knudson et al. 2010, 2353).

### *2.2.1.2 Strontium in rocks, soil, water, plants and mammalian hard tissues*

Depending on the mineral type and the absolute age of the rock type, different geological substrates exhibit a characteristic isotopic signature. The strontium isotopic variation in rocks of the Earth’s crust ranges from around 0.702 to 0.750, but higher values have been observed, especially in single minerals. Although there is large variability in detail, it can be stated that similar rock types also have similar strontium isotopic signatures. Geologically young rocks such as Tertiary and Quaternary volcanic rocks have the lowest  $^{87}\text{Sr}/^{86}\text{Sr}$  values between 0.702 and 0.706 as a result of the low Rb content and “short” time of radioactive decay of  $^{87}\text{Rb}$ . The most radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values of 0.710 to 0.750 or higher can be found in plutonic rocks, such as granite and granulites, or in metamorphic rocks such as gneiss or slate from bedrock. Intermediate values are known from marine and clastic sediments (Price et

al. 2002a, 118; Bentley 2006, 139–141; Knipper 2011, 172–174). Through the chemical weathering of rocks, the strontium signature of specific rock and mineral types is released into soils, stream- and groundwater. The released strontium is now “biologically available” and can be incorporated as a trace element into plant tissues (Knipper 2011, 174). Due to the large atomic mass of strontium, fractionation processes in sedimentary and biological processes are negligible and the  $^{87}\text{Sr}/^{86}\text{Sr}$  signature of a specific rock moves unaltered into the food chain and thus into mammalian tissues (Capo et al. 1998, 215; Blum et al. 2000, 95; Beard/Johnson 2000, 1051; Montgomery 2002, 24). However,  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of whole rocks do not necessarily reflect the biologically available strontium directly. For example, each mineral that comprises a rock has not only different  $^{87}\text{Sr}/^{86}\text{Sr}$  and strontium concentrations, but also different weathering rates. This means that more rapidly weathering minerals contribute most to the soluble strontium. Consequently, the observed  $^{87}\text{Sr}/^{86}\text{Sr}$  values for different rock types are therefore only indications for the  $^{87}\text{Sr}/^{86}\text{Sr}$  values entering the food chain (Montgomery 2002, 24; 2006, 139–141; Knipper 2011, 174). Seawater exhibits an average strontium ratio of around 0.7092 and is the result of the averaged product of weathered continental crusts worldwide (Bentley 2006, 146). Although mineral weathering is the main factor which contributes strontium to the soil, other non-local strontium sources such as atmospheric deposition from precipitation such as sea-spray, wind-borne sediments such as loess, surface- and groundwater from remote origins or fertilisers can contribute to the strontium isotopic signature of soils and thus contribute to the biologically available strontium of plants, animals and humans (Montgomery 2002, 25–27; Bentley 2006, 150–154; Britton 2009, 28).

Strontium isotopes are ingested and metabolised into human and animal biogenic tissues from their diets without fractionation. As a result of the chemical similarity, strontium substitutes passive for calcium which is the main element of biogenic apatite. Therefore, around 99% of the absorbed strontium (but only around 20% from the total dietary strontium intake) is incorporated into the carbonate hydroxyapatite lattice of bones and teeth (Montgomery 2002, 36–37; Knipper 2011, 177–178). From the dietary intake, plants have the greatest influence on the strontium isotopic composition because their strontium concentration is of several orders higher than those of meat or drinking water (Balter et al. 2008, 3981; Knipper 2011, 174–

177, Tab. 8.31). However, the strontium concentration in bioapatite is not an indicator of the amount of ingested strontium but an indicator of ingested calcium. Therefore, calcium rich dietary components contribute more to the amount of strontium and can influence the strontium isotopic composition (Montgomery 2002, 38). Strontium concentrations of modern human teeth range typically between 50–300 ppm with bone and dentine containing slightly more than enamel (Montgomery 2002, 37). Herbivores have higher concentrations than carnivores as plants contain much more strontium than meat (Montgomery 2002, 37; Knipper 2011, 174–177). Strontium concentrations vary (like strontium isotope ratios), depending on geological variations in bedrock geology, dietary choices, and extent of mineralisation (Montgomery 2002, 36–37). Strontium is incorporated into tissue during formation. Therefore, strontium isotopic compositions of tooth enamel only reflect the dietary strontium input during childhood and youth, depending on the mineralisation time of the tooth analysed.

#### *2.2.1.3 Determination of the local strontium range*

The most important requirement for the use of radiogenic strontium isotopes for the investigation of ancient human mobility is the establishment of a local strontium range for the region or site under investigation. Several different materials and approaches have been tested, but there is no ultimate method that best establishes the local strontium range for all places and individuals (Evans/Tatham 2004; Maurer et al. 2012). Each site or region as well as each community of individuals located in different temporal and spatial contexts has distinct requirements. Heterogeneity of the underlying geology, amount of imported foods, number of immigrants, and atmospheric contributions are only few examples which have to be considered. For each single case, the most appropriate method and sampling material has to be evaluated. In the following section, the different materials and approaches with their advantages and disadvantages will be summarised.

Geological maps are generally used as a starting point in order to establish the degree of the geological heterogeneity and expected  $^{87}\text{Sr}/^{86}\text{Sr}$  variations within the area of interest. Some studies have even used geological maps in order to predict  $^{87}\text{Sr}/^{86}\text{Sr}$  values (Beard/Johnson 2000; Bataille/Bowen 2012). Furthermore, numerous published  $^{87}\text{Sr}/^{86}\text{Sr}$  values of whole rock analyses are often used as a reference to estimate the broad range of  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures. Although strontium of bedrock is the

ultimate source, the expected  $^{87}\text{Sr}/^{86}\text{Sr}$  based on geological maps and of published whole rock measurements can differ significantly from the biologically available strontium (Gillmaier et al. 2009). The reason for this is that most rocks are comprised of several minerals with different  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures and concentrations and hence different weathering rates. In whole rock analysis,  $^{87}\text{Sr}/^{86}\text{Sr}$  of all minerals do equally contribute to the result, while in nature  $^{87}\text{Sr}/^{86}\text{Sr}$  of more easily weathering minerals mainly contribute to the biologically available strontium (Capo et al. 1998, 203–204; Land et al. 2000, 320; Bentley 2006, 141; Knipper 2011, 181). Therefore,  $^{87}\text{Sr}/^{86}\text{Sr}$  values of whole rock analyses only serve as a rough orientation and have to be checked and complemented by other sample types.

Soil samples are generally more appropriate than whole rock samples because they already reflect the soluble and therefore biologically available strontium which is mainly comprised of  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures from the more readily weathering minerals of a rock. However, soil samples of a site can show large variability as a result of differently advanced stages of mineral weathering at different soil depths (Bullen et al. 1997; Probst et al. 2000; Poszwa et al. 2004; Drouet et al. 2005a). Furthermore, soils are not always weathering products of the underlying bedrock. This is the case for regions which are covered by glacier deposits or in arid regions where atmospheric sources such as dust may provide an additional input (Montgomery 2010; Grupe et al. 2011, 69; Frei/Frei 2011). Further contributors to strontium in soil are ground and stream water, atmospheric deposition and anthropogenic pollution, especially fertiliser (Bentley 2006, 148–150). Different leaching preparation techniques can also lead to different  $^{87}\text{Sr}/^{86}\text{Sr}$  values of soil samples depending on the chemical reagents and the solubility of the included minerals (Knipper 2011, 181). Soils should only be used with caution for determining biologically available strontium signatures as several studies have found discrepancies between soil leachates and other geo- or biogenic materials (Sillen et al. 1998; Evans/Tatham 2004; Maurer et al. 2012).

Samples of ground and surface water are other geogenic sources for the estimation for the local strontium signature. The solute strontium isotopic composition in stream water is mainly influenced by dissolved minerals able to exchange chemically with the water in the catchment area and atmospheric inputs (Bain/Bacon 1994, 203; Capo et al. 1998, 204–205; Shand et al. 2009, 575). In comparison to soil, water has the advantage that the respective signatures are typically

based on larger catchment areas. At the same time, this may be a disadvantage when strontium is transported from remote areas with different geological characteristics (Knipper 2011, 182). Strontium concentrations in river water vary from 6 to 800 ppb (Capo et al. 1998, 204; Bentley 2006, 143). In comparison to concentrations in food, especially plants, these values are low and therefore it has been suggested that  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of water do not significantly influence the strontium isotopic composition of bioapatite (Knipper 2011, 175–177). However, this depends on the amount of water in the total dietary intake. Especially during childhood and tooth mineralisation, fluid dietary components are more important than during adult age (Montgomery et al. 2006a, 1632). Water samples may also be influenced by other strontium sources than bedrock weathering products such as by anthropogenic pollutants (Böhlke/Horan 2000; Hosono et al. 2007). Atmospheric input, such as dust, precipitation and sea spray, also influence the strontium isotopic composition of surface and ground waters (Bentley 2006, 150–154). Furthermore, it has to be taken into account that the strontium isotopic signature in smaller streams and springs is influenced by seasonal variations as a result of the different contribution of spring and precipitation water or the weathering of rocks may be influenced due to strong rainfalls (Knipper 2011, 182). Several studies have used different types of water for the prediction of biologically available strontium isotope ratios (Montgomery et al. 2006a; Evans et al. 2009; Evans et al. 2010; Voerkelius et al. 2010; Frei/Frei 2011; Bataille/Bowen 2012).

The most appropriate materials for the determination of the local strontium signature are biogenic tissues. Strontium is already biologically transformed in biogenic tissues, meaning that the variability of strontium in soils and water is averaged. Modern vegetation samples are increasingly used to determine the local biologically available strontium range (Hodell et al. 2004; Evans et al. 2010; Chenery et al. 2010; Chenery et al. 2011; Kusaka et al. 2011; Laffoon et al. 2012). However, this material is not without pitfalls, as mentioned above. First of all,  $^{87}\text{Sr}/^{86}\text{Sr}$  that enters vegetation results not only from the weathering of bedrock but also from atmospheric deposition (Kennedy et al. 2002; Poszwa et al. 2002) and can also be contaminated by anthropogenic pollutants such as fertilisers (Böhlke/Horan 2000). Furthermore, the assimilation of nutrients and hence strontium from the soil by plants depends on plant anatomy and physiology which is species specific (Poszwa et al.



2004). Therefore, tree leaves, for example, differ in  $^{87}\text{Sr}/^{86}\text{Sr}$  in comparison to ground vegetation as a result of different root systems which have access to different soil horizons with different  $^{87}\text{Sr}/^{86}\text{Sr}$  values (Nakano et al. 2001; Drouet et al. 2005a; Maurer et al. 2012). Another problem which also applies to soil samples is that plants are only representative with regards to the collection point. In regions with a heterogeneous geology, numerous plant samples have to be collected so that the whole catchment area is covered (Knipper 2011, 184).

Even more appropriate than modern plants are biogenic hard tissues from modern or archaeological animals. They obtain strontium from a larger catchment area than plants and from different sources with different  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures and are therefore more representative for human  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures. In general, local animals should be used which also obtained food and water sources locally and also reflect the diet catchment area of the human group under study (Knipper 2011, 185). Several tissues from a range of modern animals such as snail shells, rodents as well as larger wild and domestic animals have been sampled (Ezzo et al. 1997; Ezzo/Price 2002; Price et al. 2002b; Knudson et al. 2004; Knudson et al. 2005; Haverkort et al. 2008; Price/Gestsdóttir 2006). It has to be taken into account that modern animals can also be influenced by anthropogenic or atmospheric strontium sources (Maurer et al. 2012). Archaeological faunal materials have the advantage that they are not contaminated with modern strontium sources such as fertilisers. However, only tooth enamel should be analysed in order to avoid diagenetic contamination which led to the underestimation of the local strontium range. There is also a debate which faunal species should be used. Small animals such as mice may underestimate the human local signature, while cattle may overestimate it if they were kept on different fields. Good estimates have been achieved with deer, domestic pigs and dogs, but generally the use of several different faunal species is preferable (Price et al. 2002b; Bentley et al. 2004; Bentley/Knipper 2005; Bentley et al. 2005; Bentley et al. 2007). However, several aspects remain problematic because animal husbandry, food procurement and the amount of imported food are most often unknown for pre- and protohistoric communities (Knipper 2011, 185).

When biogenic tissues of plants and animals were used to establish the local strontium signature for a region, the most common approach is to calculate the mean  $^{87}\text{Sr}/^{86}\text{Sr}$  value of the measured samples plus and minus two standard deviations. Any

sample outside that range would be identified as non-local (Price et al. 2002). Even if this method is one of the most often used in order to determine the local range of a region or site, the range is rather arbitrary and not without problems, e.g. when imported animals are included, the local range will be overestimated (Shaw et al. 2009).

An estimation of the local strontium range can also be performed on the basis of the human material under study itself. In early isotopic studies, bone and dental enamel samples of the same individual were directly compared to differentiate between local and non-local individuals. This method was based on the assumption that the strontium signature of tooth enamel which is formed during the first years of life reflects the geological residence place during childhood, while bone which remodels constantly reflect the residence place of the last years and thus the local strontium value. When the values between enamel and bone differed within a certain limit (usually  $^{87}\text{Sr}/^{86}\text{Sr} > 0.001$ ), this was interpreted as an indication of residence change during a lifetime, while same values were seen as a manifestation of permanent residence at one place (Price et al. 1994a; Price et al. 1994b; Grupe et al. 1997b; Price et al. 2004; Schweissing/Grupe 2000; Schweissing/Grupe 2003b; Price et al. 2006b). This approach is only rarely used today because of high analytical costs and efforts as well as the possible lacking adaption of bone  $^{87}\text{Sr}/^{86}\text{Sr}$  to the local  $^{87}\text{Sr}/^{86}\text{Sr}$  in individuals who immigrated at a later stage in life (Knipper 2011, 182–183).

The traditional method for the differentiation of locals from non-locals – when animal remains are lacking – is the analysis of only a part of bone samples from the complete human sample set. The local strontium range is then calculated, also using the mean of the determined strontium levels  $\pm 2\text{SD}$ . The classification to local or non-local is based on the comparison between tooth enamel and the defined local range, whereas tooth enamel values outside the range are interpreted as non-local (Bentley et al. 2002; Price et al. 2002b). Even if the comparison between tooth enamel samples and the local range is more appropriate than the direct comparison between enamel and bone of one individual, there are several sources of misinterpretation, e.g. when enamel values are close to the upper or lower limit of the local range. Furthermore, bone and dentine samples that have not completely adapted the local strontium range can lead to the overestimation of the local range. Alternatively, the complete

diagenetic overprint of bones and dentine to the local soil value may lead to the underestimation of the local range (Horn/Müller-Sohnius 1999; Budd et al. 2000; Chiaradia et al. 2003; Trickett et al. 2003; Nehlich et al. 2009).

An additional method is to use human enamel values of the sample set under study. Provided the sample set is large enough, the mean value  $\pm 2$  SD of non-adult individuals can be used to determine the local range. This approach is based on the assumption that children reflect mainly local sources and residence changes haven't taken place to that point (Bentley et al. 2007). It is also possible to establish the local range by means of the enamel values of adults with a statistical approach when the samples size is large enough (Wright 2005; Tung/Knudson 2011). The values are compared to a normal distribution and outliers were stepwise excluded. This approach is especially necessary in cases where the biologically available strontium range is an inadequate proxy for human dietary strontium because the diet is derived mainly from imported food with high strontium content i.e. imported sea salt or marine resources (Wright 2005; Slovak et al. 2009). Another statistical approach arranges  $^{87}\text{Sr}/^{86}\text{Sr}$  values in ascending order and calculates the difference between each succeeding sample. Sudden breaks may indicate different strontium sources between individuals or groups and may be interpreted as indication of non-locality (Tung/Knudson 2011). However, the application of methods which solely rely on the use of human enamel for the determination of the local range run the risk that an overbalance of immigrants leads to a false estimation. Consequently, these approaches should never be used in isolation (Knipper 2011, 183; Tung/Knudson 2011, 525–253) and the most reliable results will be achieved when several approaches and materials will be used and compared with each other (Hodell et al. 2004; Evans/Tatham 2004; Maurer et al. 2012; Knipper et al. 2014).

### **2.2.2 Oxygen isotope analysis**

The application of oxygen isotope analysis of human tooth enamel for the investigation of past mobility is principally based on variations of oxygen isotopes in precipitation which is influenced by variables such as temperature, humidity, altitude, latitude and distance from the sea (Dansgaard 1964; Epstein et al. 1977; Gat 1980; Yurtsever/Gat 1981; Longinelli 1984). The oxygen isotopic composition of tooth

enamel is correlated with the isotopic composition of body water which in turn is influenced by the isotopic composition of ingested water with predictable fractionation (Longinelli 1984; Luz et al. 1984; Luz/Kolodny 1985; Bryant/Froelich 1995). A comparison of the oxygen isotopic composition of tooth enamel with the local oxygen signature of a region permits an assessment of ingested water from this area by an individual during tooth mineralisation. This, in turn, permits the identification of locals and non-locals and, hence, inferences about lifetime movements (Müller et al. 2003; Evans et al. 2006b; Evans et al. 2006a; Prowse et al. 2007; Knudson et al. 2009; Mitchell/Millard 2009; Buzon/Bowen 2010; Keenleyside et al. 2011; Wright 2012; Laffoon et al. 2013).

### *2.2.2.1 Stable oxygen isotopes*

Oxygen, the most abundant element on earth occurring in gaseous, liquid and solid compounds, has three naturally occurring stable isotopes which differ in atomic mass and abundance. The lightest,  $^{16}\text{O}$ , is the most abundant form and comprises around 99.76% of all oxygen isotopes. The two heavier isotopes  $^{17}\text{O}$  and  $^{18}\text{O}$  have abundances of ~0.04% and ~0.2% respectively (Hoefs 2009, 58). In isotopic studies the ratio between  $^{18}\text{O}$  and  $^{16}\text{O}$  is normally considered because of the higher abundance and greater mass difference. The ratio of  $^{18}\text{O}/^{16}\text{O}$  is expressed using the  $\delta$ -notation ( $\delta^{18}\text{O}$ ) in permil (‰) relative to an international accepted standard according to the following formula (Faure/Mensing 2005, 695; Sharp 2007, 17):

$$\delta^{18}\text{O} (\text{‰}) = [({}^{18}\text{O}/{}^{16}\text{O}_{\text{sample}} - {}^{18}\text{O}/{}^{16}\text{O}_{\text{standard}}) / {}^{18}\text{O}/{}^{16}\text{O}_{\text{standard}}] \times 1000.$$

While oxygen isotopes in waters or phosphates are expressed relative to the SMOW (Standard Mean Ocean Water) or the equivalent VSMOW (Vienna SMOW) standard, the PDB (Pee Dee Belemnite) or the equivalent VPDB (Vienna-PDB) scale is used in low-temperature studies of carbonate. As the original standards are exhausted, secondary standards are in use that are calibrated relative to the international standard (Hoefs 2009, 60). There is a linear correlation between both standards and the conversion can be achieved with the following equations (Hoefs 2009, 61):

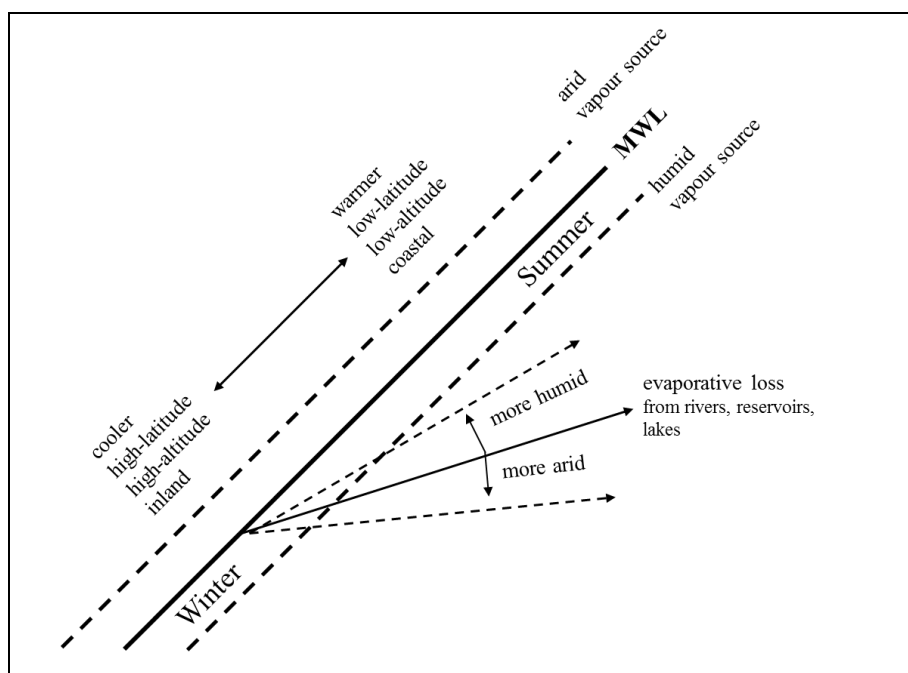
$$\begin{aligned}\delta^{18}\text{O}_{\text{VSMOW}} &= 1.03091\delta^{18}\text{O}_{\text{VPDB}} + 30.91 \text{ or} \\ \delta^{18}\text{O}_{\text{VPDB}} &= 0.97002\delta^{18}\text{O}_{\text{VSMOW}} - 29.98.\end{aligned}$$

### 2.2.2.2 Oxygen isotopes in the hydrological cycle

The application of oxygen isotopes for the investigation of archaeological related questions is primarily based on spatial and temporal differences in the stable oxygen isotopic composition of meteoric waters. Meteoric water is defined as water which has passed the hydrological cycle, including atmospheric moisture, precipitation as well as ground- and surface water derived from them (Gat et al. 2001, 181; Hoefs 2009, 136). These variations of meteoric waters result mainly from temperature dependent isotope fractionation processes which occur during phase transition of water in the global hydrological cycle (Urey 1947; Epstein et al. 1953; Craig/Gordon 1965). Given the five stable isotopes of oxygen and hydrogen ( $^1\text{H}$ ,  $^2\text{H}$ ), water molecules can have nine different isotopic compositions (isotopologues) with different physicochemical properties. When water evaporates, the lighter water molecules ( $\text{H}_2^{16}\text{O}$ ) are preferentially vaporised and the lighter oxygen isotope ( $^{16}\text{O}$ ) is enriched in the vapour phase as a result of the higher vapour pressure of the lighter molecule (kinetic and transport fractionation). In contrast, when the vapour condenses into water, heavier water molecules ( $\text{H}_2^{18}\text{O}$ ) were preferentially rained out and the heavier isotope ( $^{18}\text{O}$ ) is enriched in the liquid phase (equilibrium fractionation). These effects are more pronounced at lower temperatures and decrease when temperatures increase (Rozanski et al. 1993; Faure/Mensing 2005, 697; Sharp 2007, 74–80; McGuire/McDonnell 2007, 343–344; Hoefs 2009, 61–66).

Most of the water vapour is produced by the evaporation of surface ocean water under non-equilibrium conditions depending on, for example, sea surface temperatures, wind speed, salinity, and humidity. The resulting vapour masses are isotopically decreased in heavy water molecules in comparison to the seawater where it originates. When the vapour rises from the ocean surfaces, it cools down and rain forms when the dew point is reached. The condensation and subsequent precipitation removes water from the air mass and the residual vapour is continuously depleted in heavy isotopes. As the system of evaporation and condensation moves further inland, a rainout process induces the continual enrichment of heavy isotopes into the water phase such that the residual vapour becomes progressively more depleted in heavy isotopes (Rayleigh-like distillation) (Clark/Fritz 1997, 35–60; Gat et al. 2001, 181–195; Hoefs 2009, 137; McGuire/McDonnell 2007, 347–348).

Despite the complexity of the weather systems which are complicated by re-evaporation processes and atmospheric mixing with other vapour masses, there are two major factors controlling the isotopic composition of meteoric water. This is primarily the temperature, as it controls the fractionation process and, secondly, the proportion of the original vapour that remains after precipitation has begun (Clark/Fritz 1997; McGuire/McDonnell 2007, 348). The degree of depletion of isotopic composition of meteoric water is additionally related to several geographical and temporal parameters or “effects”, such as seasonality, humidity, latitude, altitude, and distance from the coast, as well as fluctuations in rainfall amounts (Dansgaard 1964; Epstein et al. 1977; Gat 1980; Yurtsever/Gat 1981; Rozanski et al. 1993; Gat 1996; Gat et al. 2001, 197–207; Bowen/Wilkinson 2002; Saurer et al. 2002). The main effects influencing the oxygen isotopic composition of water will be summarised in the following (see also Fig. 2.1).



**Fig. 2.1. Effects of hydrological processes on the oxygen isotopic composition of water, with more negative values near the axis origin (modified after McGlynn 2007, 82, Fig.7.7).**

Most  $\delta^{18}\text{O}$  values of precipitation over the ocean show a relatively small range ( $-0$  to  $-5\text{‰}$ ) with little seasonal change and a lack of clear correlation with temperature. With increasing distance from the ocean,  $\delta^{18}\text{O}$  values in precipitation are progressively depleted. This process is known as inland or continental effect and is controlled by the rainout of air masses. This effect shows a large variation between

different areas and seasons and correlates with the temperature gradient and depends on both the topography and the climate regime. In Europe, an average depletion of 7‰ in  $\delta^{18}\text{O}$  values is observed between the Irish coast and the Ural Mountains. The effect is more pronounced in the winter (−3‰ per 1000 km) and reduced in the summer (−1.5‰ per 1000 km) (Dansgaard 1964; Clark/Fritz 1997, 67–70; Cuntz et al. 2002; Gat et al. 2001, 202–203). With increasing distance from equatorial regions, where 60% of the atmospheric vapour originates, temperatures decrease and the degree of rainout of air masses increases. This leads to an increasing depletion of  $\delta^{18}\text{O}$  in precipitation with latitude (latitude effect). The gradient over Europe is approximately −0.5‰ per degree latitude for  $\delta^{18}\text{O}$  (Dansgaard 1964; Yurtsever/Gat 1981; Clark/Fritz 1997, 66; Gat et al. 2001, 197; McGuire/McDonnell 2007, 352). The isotopic composition of precipitation becomes also depleted in  $\delta^{18}\text{O}$  values with increasing elevation as a result of cooler average temperatures that cause increased fractionation (altitude effect). Depending on the precipitation history, the topographic situation, the degree of cooling and the perceptible moisture left, the altitude effect in  $\delta^{18}\text{O}$  of precipitation generally ranges between −0.15 and −0.5‰ per 100 m increase in elevation (Gat et al. 2001, 203–204; McGuire/McDonnell 2007, 350). The amount effect describes the relationship between the amount of precipitation/humidity, temperature and  $\delta^{18}\text{O}$  values and is defined as a relative depletion of  $\delta^{18}\text{O}$  values in precipitation by approximately 1.5‰ per 100 mm of precipitation (Dansgaard 1964; Rozanski et al. 1993; Straight et al. 2004, 247; Higgins/MacFadden 2004, 338). In Northwestern Europe, it has been observed that during convective storms  $\delta^{18}\text{O}$  can decrease by −7‰ within 1 hour (Gat et al. 2001, 204–205). In the tropics, the amount effect is responsible for seasonal differences in  $\delta^{18}\text{O}$  of precipitation rather than temperature. In contrast to higher latitudes, the  $\delta^{18}\text{O}$  values in the tropics are more negative in the summer than in the winter due to the greater amount of precipitation during the rainy season (Fricke/O’Neil 1999).

After meteoric water has fallen in liquid or solid form on the ground, there are several processes that can change the oxygen isotopic composition, so that the  $\delta^{18}\text{O}$  of surface water and groundwater can differ from the  $\delta^{18}\text{O}$  of local precipitation. Evaporation processes occurring in surface water bodies cause enrichment in  $\delta^{18}\text{O}$  in comparison to precipitation (Craig 1961; Fritz 1981; Gat 1981a; Gat 1981b; Gat 1995). Furthermore, surface waters show a reduced degree of seasonal isotopic

variability than precipitation. Additionally, water mixing with distant sourced rivers or glacial melt streams and groundwater recharge can also induce changes in  $\delta^{18}\text{O}$  values compared to precipitation (Rozanski et al. 1993; D'Angela/Longinelli 1993, 176–177; Buzon/Bowen 2010, 857).

#### *2.2.2.3 Oxygen isotopes in mammalian tissues*

Studies have shown that the oxygen isotopic composition of meteoric water is incorporated into skeletal and dental mineralised tissues of terrestrial mammals during their formation via body water (Longinelli 1984; Luz et al. 1984; Luz/Kolodny 1985; D'Angela/Longinelli 1990; Bryant/Froelich 1995; Kohn 1996; Kohn et al. 1996). The oxygen isotopic composition of body water is controlled by a mixture of oxygen inputs and outputs as well as metabolic processes. The main input sources of oxygen are drinking water, food water, metabolic water produced by the oxidation of organic food compounds and air. Oxygen leaves the body via expired breath, sweat, urine and water vapour (Luz/Kolodny 1985). However, because atmospheric oxygen has a global constant value, oxygen of body water comes mainly from liquid water (drinking water and water in plants) and to a lesser extent from organic food compounds (Longinelli 1984; Bryant/Froelich 1995; Kohn 1996).

Mammals have a relatively constant body temperature of around 37 °C and therefore, all fractionation processes during metabolism are independent of the ambient temperature. The oxygen in mammalian bioapatite precipitates in isotopic equilibrium with the body's water oxygen pool and is therefore largely controlled by the oxygen isotopic composition of body water (Luz et al. 1984; Longinelli 1984; Iacumin et al. 1996a; Iacumin et al. 1996b; Bryant et al. 1996). While the oxygen isotopic composition of drinking water is mainly reflected by that of meteoric water, the water contained in food has a complex relationship with meteoric water and can be significantly enriched in  $\delta^{18}\text{O}$  in comparison to meteoric water (Daux et al. 2008, 1138). The sources and quantities of water entering the body as liquid and from food is species-specific and varies by size, body mass, water dependency, water conservation ability, diet and metabolic rate (Longinelli 1984; Bryant/Froelich 1995; Kohn 1996; Daux et al. 2008; Podlesak et al. 2008). For most large mammals with an obligate drinking behaviour it is assumed that the  $\delta^{18}\text{O}$  values which are preserved in bioapatite components of skeletal and dental tissues mainly reflect the isotopic



signature of meteoric water of the region in which they mineralised (Luz/Kolodny 1985; Iacumin et al. 1996b; Kohn 1996; Kohn et al. 1998; Munro et al. 2008). However, larger herbivores obtaining most of their water from highly hydrated plants have increased  $\delta^{18}\text{O}$  values. This effect is increased with a decrease in relative humidity because it causes an increase in the relative amount of  $\delta^{18}\text{O}$  in surface, leaf water and the carbohydrates that they synthesise (Luz/Kolodny 1989; Luz et al. 1990; Ayliffe/Chivas 1990; Cormie et al. 1994). This effect is not visible when animals are fed dry food (Luz et al. 1984). As medium size omnivorous mammals with a moderate water turnover, humans ingest most of their water through drinking water and to a lesser extent through the consumption of local plants and animals. Therefore,  $\delta^{18}\text{O}$  of human tissues is supposed to be mainly influenced by the oxygen isotopic composition of meteoric water (Longinelli 1984; Luz et al. 1984; Levinson et al. 1987; Kohn 1996).

However, the  $\delta^{18}\text{O}$  of human tooth enamel can differ from  $\delta^{18}\text{O}$  of precipitation in the local environment for a number of reasons. One of the main contributors to variability in  $\delta^{18}\text{O}$  values of teeth from people living in the same region, between teeth of an individual and even within a tooth are seasonal and interannual climatic fluctuations (Rozanski et al. 1993; Fricke/O'Neil 1996; Wiedemann et al. 1999; Wright/Schwarcz 1999; Price et al. 2010, 22; Wright 2013, 129). Potable water can derive from several sources (rainwater collected in cisterns, river water, snow, glacial meltwater or groundwater obtained through wells) with different  $\delta^{18}\text{O}$  values (Knudson 2009, 173). For example, water in lakes, ponds and storage containers can be influenced by a reservoir effect resulting in higher  $\delta^{18}\text{O}$  values due to the evaporation of lighter isotopes or through-flowing water can bring in non-local  $\delta^{18}\text{O}$  values (Price et al. 2010, 22; Gregoricka 2013, 354). Furthermore, diet as well as food processing and beverage preparation techniques can influence the  $\delta^{18}\text{O}$  values of human tooth enamel (Daux et al. 2008; Knudson 2009, 173; Brettell et al. 2012b). Additionally, it has to be taken into account that children who are breastfed have  $\delta^{18}\text{O}$  signatures that are enriched because oxygen in body water and breast milk is enriched in  $\delta^{18}\text{O}$  in comparison to drinking water (Wright/Schwarcz 1998; Wright/Schwarcz 1999; Dupras/Tocheri 2007; Wright 2013). Finally, it cannot be excluded that some pathological conditions may affect oxygen isotope fractionation in human tissues (Reitsema/Crews 2011; Gregoricka 2013, 354).

Some of the oxygen from body water is incorporated into the oxygen containing compounds of bioapatite in tooth enamel during mineralisation where additional fractionation processes took place. Oxygen in bioapatite is present in three different locations in the crystal lattice. The main part of oxygen is located in the phosphate component ( $\text{PO}_4^{3-}$ ) and about 3.5% of weight in “structural” carbonate ( $\text{CO}_3^{2-}$ ) (LeGeros 1991; Gross/Berndt 2002; Elliott 2002; Wopenka/Pasteris 2005, 133). Around 10% of the structural carbonate substitutes for hydroxyl ( $\text{OH}^-$ ) at the  $\alpha$ -position (type A) and around 90% substitutes for the phosphate group in the  $\beta$ -position (type B) (LeGeros 1991; Daculsi et al. 1997; Gross/Berndt 2002; Elliott 2002; Wopenka/Pasteris 2005, 133–134). Another component is the “labile”  $\text{CO}_3$  which is adsorbed onto the crystal surface or incorporated into immature and less organised sites of the crystals. It is seen as diagenetically less resistant and more easily dissolved than the structural  $\text{CO}_3$  (Betts et al. 1981; Rey et al. 1991; Camacho et al. 1999; Garvie-Lok et al. 2004; Shin/Hedges 2012, 1123).

Oxygen isotopes can be measured in both the phosphate component ( $\delta^{18}\text{O}_p$ ) and the carbonate fraction ( $\delta^{18}\text{O}_c$ ) of tooth enamel. Phosphate is seen as more resistant than carbonate due to the strength of the P-O bonds and the resistance against isotopic exchange reactions at low temperatures and under inorganic conditions (Luz/Kolodny 1989, 317; Ayliffe et al. 1994, 5291; Zazzo et al. 2004a, 1). Furthermore, enamel  $\delta^{18}\text{O}_p$  is the predominant source of oxygen and appears to be relatively more sensitive to the isotopic composition of drinking water when compared to carbonate in apatite or other tissues (Podlesak et al. 2008; Martin et al. 2008; Pellegrini et al. 2011; Kirsanow/Tuross 2011). Oxygen in carbonate is derived from blood bicarbonate and therefore it was suggested that food  $\delta^{18}\text{O}$  values may make a contribution to the  $\delta^{18}\text{O}_c$  values (Kirsanow/Tuross 2011). However, several studies have proven that carbonate in tooth enamel can retain its original oxygen signatures, even in Pleistocene or Miocene contexts (Bocherens et al. 1996; Cerling et al. 1997; Lee-Thorp 2002, 443; Chenery et al. 2012). Additionally, the analysis of carbonate holds certain advantages over phosphate. It is less expensive, easier to produce, requires less material and results between labs are more comparable. Furthermore, it also provides information from carbon and oxygen isotope ratios simultaneously (Lee-Thorp 2002, 443; Pellegrini et al. 2011, 71–72; Knipper 2011, 152).

#### 2.2.2.4 Conversion from $\delta^{18}O_c$ to $\delta^{18}O_p$ and $\delta^{18}O_{mw}$

Numerous studies have shown that the measurements of  $\delta^{18}O_p$  and  $\delta^{18}O_c$  produce different but comparable results with an average offset of ~9‰ between carbonate and phosphate oxygen isotope ratios in skeletal apatite of different mammal taxa (Bryant et al. 1996; Iacumin et al. 1996b). However, the offset ranges from 7.5 to 11.4‰ in modern taxa and can also vary on a 2‰ range within one tooth (Iacumin et al. 1996a; Iacumin et al. 1996b; Bryant et al. 1996; Shahack-Gross et al. 1999; Zazzo et al. 2004a; Zazzo et al. 2004b; Martin et al. 2008; Kirsanow/Tuross 2011; Gehler et al. 2012). In order to convert carbonate into phosphate data, several equations were developed. Most studies have used the equation from Iacumin (Iacumin et al. 1996) which is based on the  $\delta^{18}O$  analysis of the phosphate and carbonate fraction of 31 tooth and bone samples from modern mammals from different climatic regions. An approximate mean difference of 9.2‰ between carbonate and phosphate data has been found. They established the following, also for humans commonly applied equation to convert  $\delta^{18}O_c$  into  $\delta^{18}O_p$  (Iacumin et al. 1996):

$$\delta^{18}O_p \text{ VSMOW} = 0.98 \times \delta^{18}O_c \text{ VSMOW} - 8.5 \text{ (} r^2 = 0.98 \text{)}.$$

However, because of species-specific variations, it is more useful to use equations which are based on human material from the same geographic and climatic region. Several studies have measured both fractions in human apatite mainly in order to test for diagenesis (Iacumin et al. 1996b; Iacumin et al. 2004; Brady et al. 2008; Tütken et al. 2008a; Metcalfe et al. 2009; Wright et al. 2010; Touzeau et al. 2013), but only a single study has established a relationship between them which was similar to that obtained by Iacumin et al. 1996 (White et al. 2000; Wright et al. 2010). The samples of this study came from Guatemala and therefore from a warm and humid region. A recent study established for the first time a direct relationship between  $\delta^{18}O_c$  and  $\delta^{18}O_p$  based on 51 human tooth enamel samples dating from the Bronze Age to the 18<sup>th</sup> century that are derived from sites between Great Britain and Mongolia and thus from relatively temperate and cold climates. The following equation was developed (Chenery et al. 2012):

$$\delta^{18}O_p \text{ VSMOW} = 1.590 \times \delta^{18}O_c \text{ VSMOW} - 9.6849 \text{ (} r^2 = 0.98 \text{)}.$$

Several studies compare their  $\delta^{18}\text{O}$  results with published  $\delta^{18}\text{O}$  values of drinking water in order to detect non-locals and to infer the place of origin of non-local individuals (Evans et al. 2006a; Millard/Schroeder 2010; Chenery et al. 2012). This is possible, because the fractionations of oxygen isotopes which take place between the ingestion of water and the deposition in enamel can be linked in a quantitative functional relationship. Several empirical species-specific equations have been developed to relate the oxygen isotopic composition of phosphate in bioapatite and that of ingested water (drinking/meteoric/ground water; Kohn/Cerling 2002). A number of equations have also been developed for humans based on  $\delta^{18}\text{O}_p$  of bioapatite from bone and tooth enamel (Longinelli 1984; Luz et al. 1984; Levinson et al. 1987; Daux et al. 2008). The first study that proved a quantitative, direct relationship between the oxygen isotopic composition of local meteoric water and human bone phosphate developed the following regression equation to convert  $\delta^{18}\text{O}_p$   $_{\text{VMSOW}}$  into  $\delta^{18}\text{O}_{\text{mw}}$  (Longinelli 1984):

$$\delta^{18}\text{O}_{\text{mw}} = 0.64 \times \delta^{18}\text{O}_p \text{ VSMOW} + 22.37 \quad (r^2 = 0.98).$$

The sample set consists of around 59 bones less than 100 years old, originating from areas between the Equator and Greenland. The meteoric water values were probably based on IAEA measurements (Longinelli 1984). Another study analysed human tooth and bone values from regions around the world, the regression on data yields the following equation (Luz et al. 1984):

$$\delta^{18}\text{O}_{\text{mw}} = 0.78 \times \delta^{18}\text{O}_p \text{ VSMOW} + 22.7 \quad (r^2 = 0.97).$$

The meteoric or local drinking water values were not measured directly but estimated from published data on precipitation (Luz et al. 1984). A further study used 40 modern teeth samples from individuals who lived at least for the first 20 years at a single locality. The regions were 15 geographical sites around the world and the local meteoric water values were measured from local drinking water. They found that the best fit linear regression yields the formula (Levinson et al. 1987):

$$\delta^{18}\text{O}_{\text{dw}} = 0.46 \times \delta^{18}\text{O}_p \text{ VSMOW} + 19.4 \quad (r^2 = 0.93).$$

One problem of this study is the modern context of the sampled individuals who lived during the 1970s and 1980s and probably obtained oxygen from imported food and

drink (Levinson et al. 1987). The differences of slope and intercept values between these studies may be the result of differences in analytical techniques, small datasets, different tissue formation times (bones and different teeth) and to a lesser extent different diets (Daux et al. 2008, 1139). The most recent study analysed 38 modern teeth from individuals who obtained local food during tooth crown mineralisation. The samples are from 12 sites between Cameroon and Greenland. They also measured tap water samples from the sites and collected OIPC data. The OIPC data and the tap water values show a good relationship not exceeding 0.8‰. They combined their own results with those of the three previous studies and developed the following linear equation (Daux et al. 2008):

$$\delta^{18}\text{O}_{\text{mw}} = 1.54 (\pm 0.09) \times \delta^{18}\text{O}_{\text{p}} - 33.72 (\pm 1.51) (r^2 = 0.87).$$

Deviation from this relationship may be due to diagenetic alteration of either the carbonate or phosphate component, acetic acid treatment of carbonate, or differences in the portion of the tooth crown sampled for the two analyses. In general, diagenetic changes should lead to decreased  $\delta^{18}\text{O}$  in enamel as a result of isotopic exchange with soil water which has lower  $\delta^{18}\text{O}$  values than teeth (Knipper 2011, 153).

However, as a result of the several sources of variation, the still unclear fractionation between carbonate and phosphate (Martin et al. 2008; Pellegrini et al. 2011) the not fully understood relationship between drinking water and human skeletal phosphate oxygen (Longinelli 1984; Luz et al. 1984; Levinson et al. 1987; Daux et al. 2008), and the errors which are associated with regression equations (Pollard et al. 2011b) it is recommend to rely on direct comparisons with published empirical oxygen isotope values obtained from skeletal materials (Müldner et al. 2011; Pollard et al. 2011b; Laffoon et al. 2013).

### **2.2.3 Carbon isotope analysis**

The application of carbon isotope analysis is based on variations in the relative abundance of the carbon isotopic composition in terrestrial and aquatic ecosystems as a result of differences in photosynthetic pathways of plants and environmental factors influencing them as well as different carbon sources. These values were transmitted into human and faunal tissue via food and provide information on the diet and the specific environment where the food was obtained of an individual and a community.

Carbon isotope analysis was mainly widely used for palaeodiet studies (e.g. Knipper et al. 2012b). However, it can also be used to infer differences between individuals and groups, indicating different origins rather than different diets (Hakenbeck et al. 2010).

#### *2.2.3.1 Carbon stable isotopes*

The relevant stable naturally occurring carbon isotopes are  $^{12}\text{C}$  and  $^{13}\text{C}$ . The lighter isotope  $^{12}\text{C}$  has an abundance of 98.93% and the heavier  $^{13}\text{C}$  isotope of 1.07% (Hoefs 2009, 48). As with oxygen, the ratio of  $^{13}\text{C}/^{12}\text{C}$  is expressed using the  $\delta$ -notation ( $\delta^{13}\text{C}$ ) in permil (‰) relative to the standard VPDB (Vienna Pee Dee Belemnite) according to the following formula (Faure/Mensing 2005, 753):

$$\delta^{13}\text{C} (\text{‰}) = [(\frac{^{13}\text{C}}{^{12}\text{C}}_{\text{sample}} - \frac{^{13}\text{C}}{^{12}\text{C}}_{\text{standard}}) - 1] \times 1000.$$

#### *2.2.3.2 Carbon isotopes in the environment*

Carbon is as a basic element of all organic compounds the principal ingredient of the biosphere. Furthermore, it occurs in different forms in the atmosphere (e.g.  $\text{CO}_2$ ,  $\text{CH}_4$ ), in soils, fossil fuel, carbonate rocks, and in the oceans mainly as dissolved bicarbonate (Faure/Mensing 2005, 753–754; Sharp 2007, 149–153). Terrestrial plants use carbon dioxide from the atmosphere for the production of oxygen during photosynthesis. Atmospheric carbon has a contemporary  $\delta^{13}\text{C}$  value of around  $-8\text{‰}$  (Keeling et al. 2010). In pre-industrial times this value was higher due to the fact that since the industrial revolution the increased burning of fossil fuels and forest materials introduced  $\text{CO}_2$  with decreasing  $\delta^{13}\text{C}$  values into the atmosphere which results in decreasing  $\delta^{13}\text{C}$  values for atmospheric carbon. Investigations of ice cores have shown that during the time from 400 to 600, the  $\delta^{13}\text{C}$  value of atmospheric carbon was around  $-6.5\text{‰}$  (Francey et al. 1999, 188, Fig. 9; MacFarling Meure et al. 2006, 3, Fig. 2). Atmospheric carbon is assimilated into plant tissues via  $\text{CO}_2$  diffusion and further dissolution and carboxylation. During these processes, kinetic isotope effects occur which led to the discrimination against the heavier  $^{13}\text{C}$  isotope and thus in decreased  $\delta^{13}\text{C}$  values in comparison to the atmosphere. The extent of this discrimination depends on the type of photosynthesis (O’Leary 1981; O’Leary 1988). The most widely distributed pathways are the  $\text{C}_3$  (Calvin-Benson cycle) and  $\text{C}_4$  (Hatch-Slack) cycles.

The C<sub>3</sub> cycle includes several reactions in which the carbon from CO<sub>2</sub> is transformed into stable organic products. In short, CO<sub>2</sub> diffuses through the stomata, is dissolved in leaf water and enters the mesophyll cells where the enzyme ribulose biphosphate carboxylase/oxygenase (Rubisco) transforms it into two molecules phosphoglycerate (PGA) which has three carbon arms. Plants which follow this photosynthetic pathway are therefore called C<sub>3</sub> plants. The main part of PGA is recycled into ribulose biphosphate. The remaining PGA is used for the production of carbohydrates. Because Rubisco strongly discriminates against <sup>13</sup>C in favour of lighter <sup>12</sup>C isotopes, the values of C<sub>3</sub> plants are extremely depleted in <sup>13</sup>C (Ehleringer/Cerling 2002; Hoefs 2009, 51). Almost all plants in temperate climates, including most food-relevant plants in pre-industrial Central Europe such as most fruits, vegetables, legumes, nuts, wheat and barley, follow the C<sub>3</sub> pathway (Lee-Thorp 2008). C<sub>3</sub> plants exhibit a large range of δ<sup>13</sup>C values between -20 to -37‰ with an average value clustering around -26.5/-28.5‰ (Kohn 2010, 2). Extreme δ<sup>13</sup>C values below -31.5‰ occur under closed forest canopies, while highest δ<sup>13</sup>C values above 23‰ have been observed in water-stressed ecosystems such as dry deserts with a mean annual precipitation under 10 mm (O'Leary 1988; Cerling et al. 1997, 153; Kohn 2010, 1; 2, Fig. 1B).

The C<sub>4</sub> photosynthetic pathway is a biochemical and morphological modification of C<sub>3</sub> photosynthesis. Before the carbon is decarboxylated and refixed in the normal C<sub>3</sub> cycle in the interior cells within the leaf (bundle sheath cell), it is incorporated in mesophyll cells surrounding the bundle sheath cells. In the mesophyll cells, the enzyme phosphoenol pyruvate (PEP) carboxylase fixes CO<sub>2</sub> into oxaloacetate, an acid with four carbon arms. These processes result in decreased δ<sup>13</sup>C values in comparison to the atmosphere, but the discrimination against <sup>13</sup>C is not as extreme as for C<sub>3</sub> plants (Ehleringer/Cerling 2002, 186; Marshall et al. 2008, 23-24; Hoefs 2009, 51). C<sub>4</sub> plants, including food-relevant plants such as maize, sugar cane, some millets, sorghum and tropical grasses, are better adapted to arid conditions and are absent or very limited in environments with a temperate or cold growing season as in Europe (Lee-Thorp et al. 1989; Ehleringer et al. 1997). They show a more restricted δ<sup>13</sup>C range between -16 to -9‰ with a mean of around -14‰ because they do not exist under canopies and are better adapted to arid conditions (Smith/Epstein 1971; Marshall et al. 2008, 23-24).

The photosynthetic pathway is the major factor influencing the  $\delta^{13}\text{C}$  signature of plants but there are also several environmental factors which can modify the isotopic signatures of plant tissues through their influence on either leaf conductance or photosynthetic rate or both. These factors include water availability, plant water-use efficiency, relative humidity, temperature and altitude, light intensity, nutrient availability, salinity, soil quality, etc. (O’Leary 1981; Farquhar et al. 1989; Tieszen 1991; Dawson et al. 2002; Ferrio et al. 2003; Marshall et al. 2008, 24–27; Hoefs 2009, 51–52). In addition, individual plants or plant fractions can also have different  $\delta^{13}\text{C}$  values depending on their biochemical and anatomical construction (Heaton 1999, 639–641; Ferrio et al. 2003, 88–90; Cernusak et al. 2013).

Central Europe is dominated by  $\text{C}_3$  plants and  $\delta^{13}\text{C}$  varies according to the extent of forest cover which is termed “canopy effect”. Plants growing under a closed canopy have lower  $\delta^{13}\text{C}$  values than plants growing at the top of the canopy or in open environments and the difference can reach up 5‰ in boreal and temperate contexts (van der Merwe/Medina 1991; Drucker et al. 2008; Bonafini et al. 2013). Furthermore, shifts of  $\delta^{13}\text{C}$  values of plants can also be due to altitude. An increase of about 1.1‰ was measured per 1000 m increase in altitude (Körner et al. 1991). Additionally, it has been shown that  $\delta^{13}\text{C}$  values become less negative with increasing temperatures and more negative with increasing precipitation and humidity (Van Klinken et al. 1994; Kohn 2010).

Marine and freshwater systems are more complex than terrestrial ecosystems because they are shaped by more carbon sources. In addition to atmospheric  $\text{CO}_2$ , aquatic carbon sources include dissolved inorganic bicarbonate  $\text{CO}_2$  and organic carbon incorporated into rivers and oceans. These sources are often enriched relative to atmospheric  $\text{CO}_2$ , especially in ocean settings. Most aquatic plants also use the  $\text{C}_3$  pathway but bring about  $\delta^{13}\text{C}$  values which are increased in comparison to terrestrial  $\text{C}_3$  plants (Chisholm et al. 1982; Dufour et al. 1999; Richards/Hedges 1999; Barrett et al. 2008; Keaveney/Reimer 2012). However, aquatic sources exhibit  $\delta^{13}\text{C}$  values that are intermediate between  $\text{C}_3$  and  $\text{C}_4$  and therefore it is difficult to distinguish between aquatic and terrestrial plants without additional biochemical evidence from collagen. Freshwater fish has  $\delta^{13}\text{C}$  values typically below  $-22\text{‰}$  (Dufour et al. 1999; Müldner/Richards 2005).



### 2.2.3.3 Carbon isotopes in mammalian tissues

The carbon isotopic composition of consumed foods is incorporated into mammalian tissues during formation. The  $\delta^{13}\text{C}$  signature of a certain body tissue reflects the average metabolised dietary carbon of an individual. Depending on the tissue, its formation time and its metabolic pathway reflect different dietary information at different temporal life stages. The carbon that forms collagen comes mainly but not exclusive from the dietary protein portion, while the structural carbon that builds bioapatite derives from blood plasma bicarbonate and reflects a mixture of dietary protein, carbohydrates and fats (Ambrose/Norr 1993; Tieszen/Fagre 1993; Hedges 2003; Howland et al. 2003; Jim et al. 2004; Kellner/Schoeninger 2007; Warinner/Tuross 2009; Froehle et al. 2010; Fernandes et al. 2012). Furthermore,  $\delta^{13}\text{C}$  signatures of bone bioapatite and collagen reflect the average dietary input of an individual during recent years as a result of the constant remodelling of bones. The time frame depends on the analysed type of bone but also on physiological aspects. In turn, dentinal collagen and enamel apatite represent only a restricted chronological time frame during childhood and youth depending on the tooth analysed because of the lack of remodelling after formation (Sealy et al. 1995). The  $\delta^{13}\text{C}$  of the consumed food is not the same as in the tissue under investigation. Additional isotopic fractionations take place between different dietary components, resulting in an offset in  $\delta^{13}\text{C}$  values between diet and skeletal tissue. This shift has been investigated for several animal species and is expected to increase about 5‰ between plant food and the collagen of herbivores (Bocherens 2002, 67–68, Fig. 4.1; Lee-Thorp 2008, 928). Subsequent enrichment of bone collagen  $\delta^{13}\text{C}$  between members of two adjacent trophic levels measures 0 to 2‰ (Bocherens/Drucker 2003; Drucker/Henry-Gambier 2005; Lee-Thorp 2008; Bocherens et al. 2011). The degree of carbon isotopic fractionation between diet and enamel bioapatite in carnivores is around +10‰ and in herbivores around +14‰ (Bocherens 2002, 67–68, Fig. 4.1; Lee-Thorp 2008, 928). For humans, the enrichment factor between diet and apatite is unknown but is estimated between ca. +11–12‰ (Hedges/van Klinken 2002; Passey et al. 2005; Prowse et al. 2007).

## II. MATERIAL & METHODS

### 3 Region and sites

#### 3.1 The northern Upper Rhine area

##### 3.1.1 Location and natural conditions

The research area is situated on the left bank of the Rhine in the northern part of the Palatinate region in close vicinity to the Rhine Hesse region in the federal state Rhineland-Palatinate in Southwest Germany. According to the regional classification of Germany, the research area belongs to the major unit group of the Northern Upper Rhine Plain which is limited to the northwest by the Saar-Nahe Hills and to the southwest by the Haardt Mountains. To the east on the right bank of the Rhine, the Northern Upper Rhine Plain borders on the Hessian Frankian Uplands and merges into the Rhine-Main Basin to the northeast. The sites are situated at the transition of two major units, the Anterior Palatinate Lowland (*Vorderpfälzer Tiefland*) in the north and the Rhenish-Hessian table and hill land (*Rheinhessisches Tafel- und Hügelland*) in the south<sup>2</sup>.

The present-day morphology of the Anterior Palatinate Lowland is characterised by an alteration of small, elongated and flat ridges covered by loess and flat valleys which are the result of the fluvial incision of rivers draining from the Palatinate Forest. While the ridges are mainly agricultural areas, the alluvial fans, which can extend over large areas, comprise the largest coherent wetlands, forests and grassland areas of the Upper Rhine Valley. Near Frankenthal and Worms parallel to the Rhine River there are large plains (e.g. Frankenthaler Terrace) which are, together with the borderlands of the Rhine depression, the focus of olericulture. Heights of the Anterior Palatinate Uplands range from 160–170 m NHN in the west to around 95 m NHN in the east on the plains (Leser 1964, 69–104; May 1990, 86–94; Peters/van Balen 2007). The Rhenish-Hessian table and hill land is an independent entity on the Northern Upper Rhine Plain. As a result of geological uplifting processes and erosion, the present-day morphology is characterised by an alternation of plateaus with heights of more than 270 m NHN covered by fluvial sands and loess as well as valleys or

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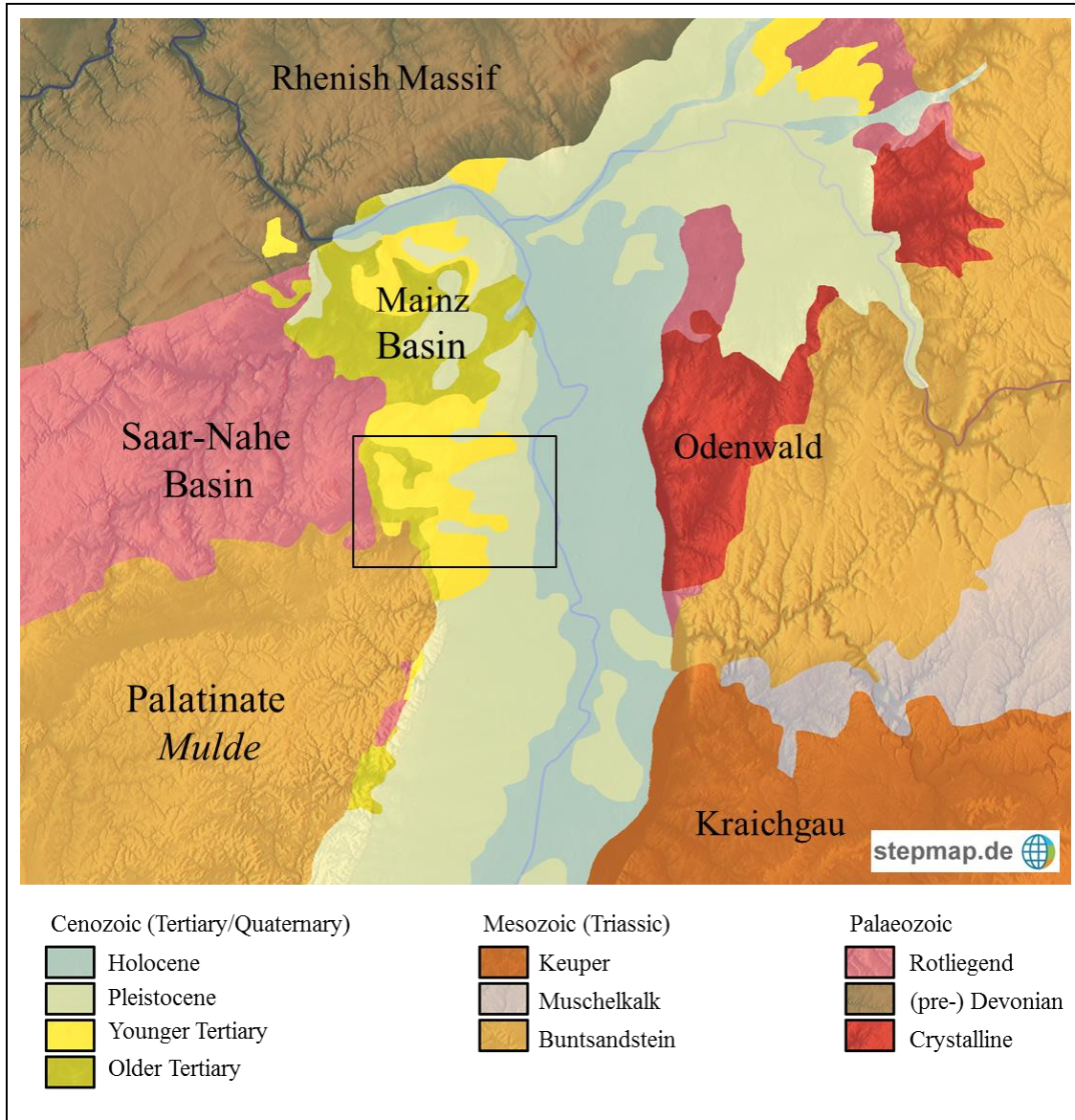
<sup>2</sup> <http://www.luwg.rlp.de/Aufgaben/Naturschutz/Grundlagendaten/Naturraeumliche-Gliederung/> (03.01.2014); [http://atlas.umwelt.hessen.de/servlet/Frame/atlas/naturschutz/naturraum/karten/m\\_3\\_2\\_1.htm](http://atlas.umwelt.hessen.de/servlet/Frame/atlas/naturschutz/naturraum/karten/m_3_2_1.htm) (03.01.2014).

hollows. As a result of fertile soils, the area is characterised by agriculture and viniculture and therefore only sparsely wooded (Preuss 2003, 6–14; Peters/van Balen 2007).

Geologically, the research area is part of the Upper Rhine Graben and the Mainz Basin (Fig. 3.1 and Fig. 10.1). The Upper Rhine Graben is a tectonic rift valley or “graben” structure between the Rhenish Massif in the north and the Jura Mountains in the south with a length of around 300 km and an average width of approximately 36 km. The evolution of the Upper Rhine Graben started around 45 million years ago in the Eocene with several episodes of subsidence and it is still active today. The rift valley was filled with fluvial, lacustrine and marine Cenozoic sediments which can reach a thickness of around 3000 m. During the Pliocene and the Quaternary, mainly fluvial sediments of the Rhine and its tributaries were deposited which show large thickness variations from around 500 m in the east in the vicinity of Heidelberg to few tens of meters towards the western and northern borders of the Upper Rhine Graben (Landesamt für Geologie und Bergbau 2005, 193–200; Walter 2007, 436–440; Peters 2007, 38; Weidenfeller 2013, 72–78). The Mainz Basin is a roughly triangular Tertiary basin located at the northwestern end of the Upper Rhine Graben. Originally, it was a part of the graben but since the Late Oligocene it developed independently and was included in the episodic uplift of the Rhenish Massif. The thickness of Cenozoic graben fill, which consists of fluvial, lacustrine and marine sequences, is only a few hundred meters deep as the Mainz Basin has subsided less than the Upper Rhine Graben. At present, Tertiary sediments (clay, sands, limestones, marls and gravels) are partly covered by Quaternary deposits such as fluvial sediments of the Rhine and its tributaries, aeolian deposits such as loess and drifting sand as well as slope wash deposits (Horn et al. 1997, 200–219; Walter 2007, 441–443; Peters 2007, 37; Schäfer 2012, 3–9; Weidenfeller 2013, 71–72).

The Upper Rhine Graben and the Mainz Basin are flanked by uplifted mountain ranges. The western shoulder areas are formed by the Saar-Nahe Hills with Permocarbanian sedimentary (silt- and sandstones, conglomerates) and magmatic rocks in the north and the Palatinate Forest (*Pfälzer Mulde*) in the south with Buntsandstein (Landesamt für Geologie und Bergbau 2005, 73–186; Haneke 2013, 9–19; Dittrich 2007, 20–34). The eastern shoulder area, the Odenwald, is comprised of crystalline basement rocks which are around 500 million years old in the western part and of Buntsandstein in the eastern part (Walter 2007, 227–230). The northern border

of the Upper Rhine Valley and the Mainz Basin is the Rhenish Massif which is mainly comprised of Devonian rocks clay, silt and sandstone (Landesamt für Geologie und Bergbau 2005, 15–73; Walter 2007, 177–205) (Fig. 3.1).



**Fig. 3.1.** Geological map of the northern Upper Rhine Valley and adjacent areas.

The main receiving water course in the research region is the Rhine River. Several streams originating in the Buntsandstein and Rotliegend area of the western mountain regions pass through the lowland and empty into the Rhine. In the Upper Rhine lowland, groundwater lies only 1.5–2 m under the terrain, while on the loess plateaus groundwater is often not reached until 6–10 m in depth. Confined groundwater has the same level as the streams provided it is not covered by

waterproof layers. As a result of the fault-block structure of the Upper Rhine Valley there is no uniform groundwater horizon (May 1990, 96).

The Rhineland-Palatinate is divided into several groundwater landscapes. These are regions with homogenous hydrogeological and morphological features and groundwaters with typical hydrochemical characteristics as a result of the geological underground (see Fig. 3.5). Investigations of water samples have shown that the shallow ground waters of the Rhine Plain are contaminated with fertiliser and waste water. The highest strontium concentrations were measured in Tertiary marls, clay and siltstones with values of  $1.063\mu\text{g/l}$ . High strontium concentrations above  $500\mu\text{g/l}$  were also measured in Quaternary groundwaters. The lowest values of  $63\mu\text{g/l}$  were measured in the Buntsandstein area (Blitzer et al. 2012).

The Upper Rhine lowland is a climatically favoured region with some of Germany's warmest and driest climates. Today, the average annual temperature measures approximately  $11\text{ }^{\circ}\text{C}$ . The warmest month is July with an average temperature of around  $20\text{ }^{\circ}\text{C}$  and the coldest is January with an average temperature of  $0.7\text{ }^{\circ}\text{C}$ . The annual average precipitation amounts to around 625 mm. The lowest annual average precipitation with less than 550 to 600 mm was measured in the area of the Frankenthaler Terrace and the hilly area of Alzey. In the western peripheral areas near the highlands, annual precipitation increases to 600 mm or more and the temperatures are ca.  $1\text{ }^{\circ}\text{C}$  colder. In the highlands of the Palatinate Forest, the average annual temperature is around  $7\text{ }^{\circ}\text{C}$  with an annual average precipitation of 800 to 1000 mm. To the east towards the Odenwald, precipitation also increases as a result of orographic rainfall at the eastern scarp of the Upper Rhine Valley (May 1990, 95–95; Kampf/Schwebler 2005, 12)<sup>3</sup>.

### 3.1.2 Published biogeochemical signatures

#### 3.1.2.1 Radiogenic strontium isotope signatures

The first study using archaeological skeletal material from sites located in the northern Upper Rhine Valley was conducted at the beginning of 2000 (Price et al. 2001; Bentley et al. 2002). Samples include Neolithic human bone and tooth material from the *Linearbandkeramik* cemeteries of Flomborn and Schwetzingen. The site

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<sup>3</sup> <http://www.kwis-rlp.de/index.php?id=6867> (03.01.2014)

Flomborn is situated in the Rhine Hesse region approximately 5 km north of the early medieval site of Bockenheim. The area is built of Tertiary layers of the Mainz Basin which is covered by a Pleistocene loess layer. The site was excavated at the turn of the century, and has therefore not been contaminated with modern fertiliser (Bentley et al. 2004, 365–366). Human bone samples were used in order to determine the local strontium range. The  $^{87}\text{Sr}/^{86}\text{Sr}$  ranged from 0.70973 to 0.71019 (mean =  $0.70995 \pm 0.00019$ ,  $n = 7$ ). The local strontium signature at the site was defined within two standard deviations of the average and ranges between 0.70957 and 0.71033 (Price et al. 2001, 600; Bentley et al. 2002, 800). In contrast, Schwetzingen is located on fluvial sediments of the Rhine River without loess cover. Six human bone samples yielded  $^{87}\text{Sr}/^{86}\text{Sr}$  values from 0.70907 to 0.71001 (mean =  $0.70941 \pm 0.00036$ ) and the local strontium range measured between 0.70868 and 0.71013 (mean  $\pm 2\text{SD}$ ) (Price et al. 2001, 600; Bentley et al. 2002, 800). The cemetery was excavated in 1988 and therefore modern fertilisers may have contaminated the bone samples resulting in lower  $^{87}\text{Sr}/^{86}\text{Sr}$  values in comparison to enamel values (Price et al. 2001, 600; Bentley et al. 2004, 369). Modern snail shells collected at Flomborn exhibit a mean  $^{87}\text{Sr}/^{86}\text{Sr}$  value of  $0.70912 \pm 0.00047$  ( $n = 3$ ), while modern mice samples from Schwetzingen show a mean  $^{87}\text{Sr}/^{86}\text{Sr}$  of  $0.70883 \pm 0.00015$  ( $n = 2$ ) (Bentley et al. 2003, 474, Tab. 1; Bentley et al. 2004, 369; 370, Fig. 3). These values are lower than the  $^{87}\text{Sr}/^{86}\text{Sr}$  of bone samples at each respective site and it is possible that these mice and snails are influenced by less radiogenic atmospheric and anthropogenic strontium sources (Bentley et al. 2004, 369).

More strontium isotope values from archaeological skeletal material are available from the region around Frankenthal, which is in the vicinity of the site of Eppstein. A complete early medieval equid skeleton, probably a mule, was found in sandy-silty deposits of an old sidearm of the Rhine in the vicinity of Frankenthal in the Rhine Valley. The well-preserved metatarsal bone produced a  $^{87}\text{Sr}/^{86}\text{Sr}$  value of 0.70966 with a strontium concentration of 1313 ppm (Tütken 2003, 324, Tab. V.2; Tütken et al. 2004, 104). It is assumed that the Carolingian mule spent its life in the vicinity of Frankenthal or in a lowland region further north, but did not imbibe large amounts of water directly from the Rhine (Tütken et al. 2004, 105). In the same study, Pleistocene mammal bones and a tooth deposited in Rhine gravel (gravel quarry Büttel, south of Gimbsheim) were investigated. The well-preserved inner part of the compact bones of five individuals ranges from 0.70891 to 0.70933

with concentrations between 264 and 595 ppm. Diagenetic alteration of the exterior of the bone and dentine samples resulted in lower strontium values and higher strontium concentrations in comparison to well-preserved proportions of the bone which have been contaminated with water from the Rhine River (Tütken 2003, 324, Tab. V.2; Bentley 2006, 104–105).

Additional local strontium values for a loess-covered region of the Upper Rhine Valley are available from the Neolithic pit-enclosure Herxheim in the south of the Palatinate. The mean  $^{87}\text{Sr}/^{86}\text{Sr}$  value of an unknown number of archaeological faunal tooth enamel remains recovered from the site is  $0.70953 \pm 0.00008$  ( $1\sigma$ ). The local range of 0.70937–0.70969 was determined by the mean  $\pm 2\text{SD}$  (Turck et al. 2012, 156–160).

In a project mapping the biologically available strontium, carbon, and oxygen signatures of prehistoric Southern Germany by means of dental enamel of pigs, additional sites from the Upper Rhine Valley were analysed (Bentley/Knipper 2005). The site of Goddelau is situated on the eastern bank of the Rhine ca. 35 km northeast from the site of Bockenheim. Three Neolithic pigs from the site were analysed. Two of them are supposed to show local  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures (0.70863 and 0.70953) while the third is interpreted as non-local with a value of 0.71568 (Bentley/Knipper 2005, 635–637, Tab. 1, Tab. 2). Pig teeth from different time periods were sampled from two other sites at a more southern part of the Upper Rhine Valley in Sasbach and Bischoffingen (Kaiserstuhl). Four supposed local individuals show an average of  $0.7090 \pm 0.0008$  (Bentley/Knipper 2005, 635–637, Tab. 1, Tab. 2). In combination with other pig samples from loess and alluvial lowland areas in Southern Germany, they determined a biologically available strontium signature for the Rhine, Main, Neckar and pre-Alpine lowland between 0.70860 and 0.71030 (Bentley/Knipper 2005, 637).

In addition to the above-mentioned mice and snail shell samples from Schwetzingen and Flomborn, only few other modern samples from the Upper Rhine have been analysed. Modern snails from sites at the foothills of the Odenwald in the Rhine Valley (Schönau, Dossenheim, Schriesheim, Hohensachsen) have a mean strontium value of  $0.70923 \pm 0.00012$  ( $n = 6$ ) (Bentley et al. 2003, 475, Tab. 1; Price et al. 2003, 43, Tab. 8). Strontium isotope values which were measured from vine samples originating from vineyards in Rhine Hesse yielded values between 0.709 and 0.7105 (Horn et al. 1997, 36, Fig. 4). Sediment or soil samples of vineyards in

Rhineland-Palatine range from 0.70900 to 0.71000 (Price et al. 2003, 40, Tab. 3). Water samples from the Rhine at sampling locations in the northern Upper Rhine Valley (Guntersblum and Petersau) have  $^{87}\text{Sr}/^{86}\text{Sr}$  values of 0.70870 and 0.70880 respectively (Buhl et al. 1991, 340, Tab. 2). These samples are most probably polluted by industrial waste water because, non-polluted water samples of the Rhine have  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures between 0.70830 and 0.70850 and it has therefore been suggested that the bulk of dissolved strontium of the Upper Rhine is derived from Miocene marine sediments of the Alpine molasses (Buhl et al. 1991, 342–346; Tricca et al. 1999, 145–146). The slightly more radiogenic values above 0.70850 are changed by the input of waste products and especially by industrial pollution and fertiliser in the area between Mannheim and Frankfurt (Buhl et al. 1991, 346; Tricca et al. 1999, 143–144). Tributaries of the Rhine River in the vicinity of the research area, such as Neckar (0.70860) and Main (0.70880), have relatively non-radiogenic values because of their catchment area which is composed of Mesozoic sedimentary rocks. In comparison, the Nahe River (0.71110) has more radiogenic values as this tributary originates from Palaeozoic rocks of the Rhenish Massif (Buhl et al. 1991, 341–344; 340 Tab. 2; Tab. 3; Tütken et al. 2004, 104–105). Aquifers of the Rhine Plain are built on Tertiary marls as well as Pliocene and Quaternary alluvial deposits and loess. Groundwater measurements of the soluble fraction in the southern part of the Upper Rhine Valley between Colmar and Mulhouse have  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures of around  $0.70870 \pm 0.00007$  ( $n = 14$ ) and strontium concentrations of  $349 \pm 81 \mu\text{g/l}$  (Tricca et al. 1999, 142, Tab. 1). This is in correspondence with  $^{87}\text{Sr}/^{86}\text{Sr}$  values of Rhine water  $0.70847 \pm 0.00009$ ,  $355 \pm 59 \mu\text{g/l}$  ( $n = 19$ ) in this area and is indicative of extensive exchange between these hydrological systems (Tricca et al. 1999, 143). Upper Rhine Plain rivers in this region have partly more radiogenic values ( $0.70970 \pm 0.00110$ ,  $135 \pm 83 \mu\text{g/l}$  ( $n = 48$ ) as a result of exchange with streams of the Vosges Mountains ( $0.71670 \pm 0.00430$ ,  $28 \pm 25 \mu\text{g/l}$  ( $n = 25$ )) (Tricca et al. 1999, 142–144; 142, Tab. 1). Untreated suspended loads of the Rhine in the southern part of the Upper Rhine Valley have more radiogenic values of 0.70990 to 0.71170 than the Rhine water (Tricca et al. 1999, 145, Tab. 2). Two loess samples from the Kaiserstuhl exhibit  $^{87}\text{Sr}/^{86}\text{Sr}$  of  $0.70956 \pm 0.00030$  to  $0.71001 \pm 0.00050$  with strontium concentrations of 302 and 360 ppm respectively (Taylor et al. 1983, 1902, Tab. 4).

In conclusion, based on published  $^{87}\text{Sr}/^{86}\text{Sr}$  values from archaeological bone and enamel, modern snail shells as well as water and soil samples, the local strontium



range in the northern Upper Rhine Valley does not exceed the range between at maximum 0.70986 and 0.71020. There is also the tendency that samples from loess areas are slightly elevated in comparison to samples from sites without loess cover. It has to be taken into account that modern fauna as well as water and soil samples can be influenced by atmospheric or anthropogenic strontium sources. A summary of the strontium values from the studies described above, are presented in Fig. 3.2.

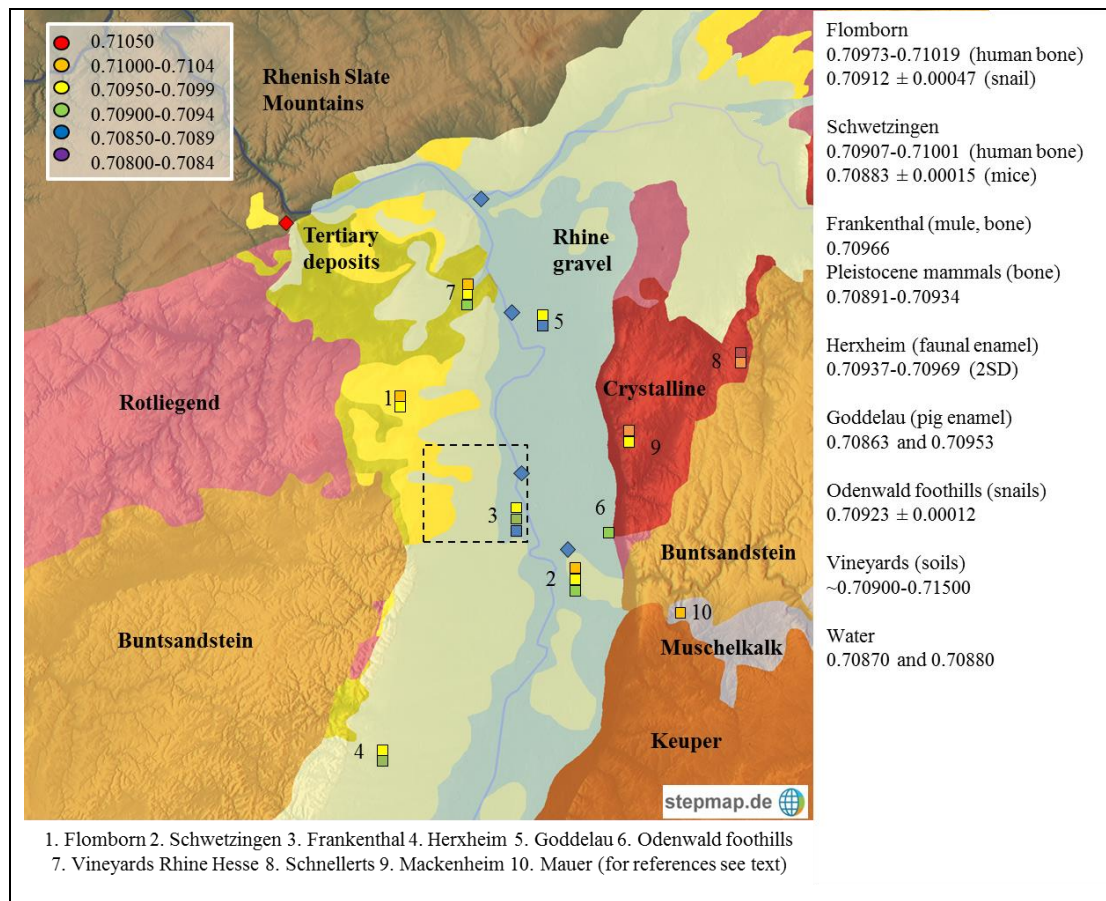


Fig. 3.2.  $^{87}\text{Sr}/^{86}\text{Sr}$  from sites in the Upper Rhine area.

Measurements of  $^{87}\text{Sr}/^{86}\text{Sr}$  from adjacent upland areas are only available from the eastern side of the Rhine Valley. Pig tooth enamel from a medieval site in Schnellerts in the crystalline Odenwald exhibit  $^{87}\text{Sr}/^{86}\text{Sr}$  values of 0.71020 and 0.71110 (Bentley/Knipper 2005, 635–637, Tab. 1, Tab. 2). Modern snails from sites in the Odenwald have average  $^{87}\text{Sr}/^{86}\text{Sr}$  values of  $0.71061 \pm 0.00029$  ( $n = 4$ ) (Price et al. 2003, 42, Tab. 7) and  $0.70985 \pm 0.00065$  ( $n = 4$ ) (Bentley et al. 2003, 475, Tab. 1). A modern human tooth from Mauer has a value of  $0.71070 \pm 0.00020$  (Horn et al. 1994, 361, Tab.1). An extensive collection of all available strontium isotope values of different materials from all geological units in Southwest Germany are available in

Knipper 2011. An overview about the differences between geological and biological strontium of the main geological units of Southwest Germany is presented in Fig. 3.3.

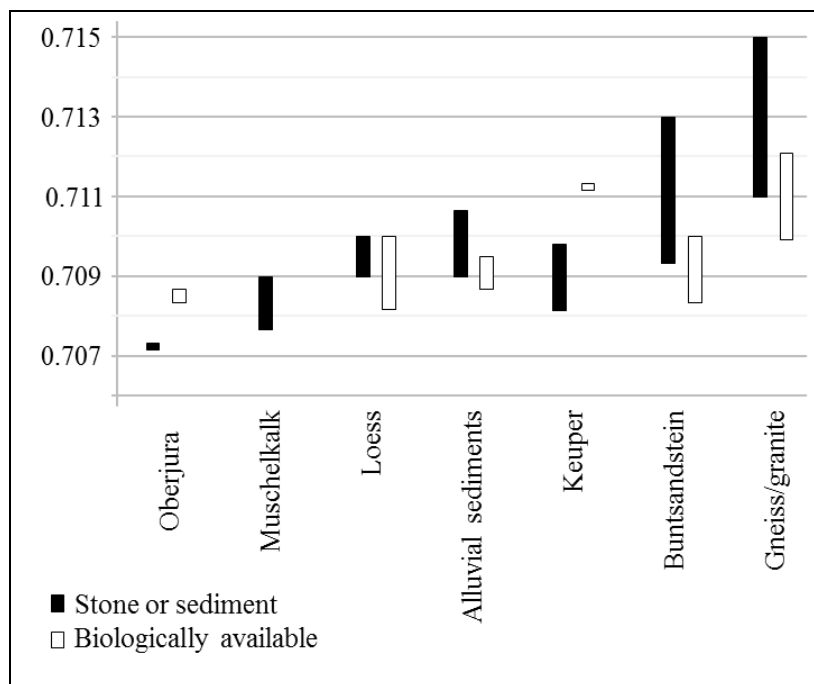


Fig. 3.3.  $^{87}\text{Sr}/^{86}\text{Sr}$  from geological and biological sources in Southwest Germany (modified after Price et al. 2006b, Fig. 6).

### 3.1.2.2 Oxygen isotope signatures

In contrast to strontium isotopes, which do not fractionate and are robust over archaeological time scales, oxygen isotopes present a different case. The determination of the local oxygen isotope range and especially its comparison with other oxygen isotopic data is problematic for several reasons (see 2.2.2.4.).

Most studies use published  $\delta^{18}\text{O}$  values of modern waters from precipitation, streams or groundwater to get an impression of the regional and seasonal variation of a region. The most important source of information about  $\delta^{18}\text{O}$  values of precipitation is the GNIP database (Global Network of Isotopes in Precipitation) published by the IAEA (International Atomic Energy Agency) and the WMO (World Meteorological Organisation). In this online accessible database<sup>4</sup>, oxygen values of precipitation from more than 800 meteorological stations, which were collected worldwide from 101 countries since 1961, are available. In Germany, a total of 20 stations are present. The stations, which are located near to the research area, are found in Koblenz in the north and Karlsruhe in the south. The  $\delta^{18}\text{O}$  values of precipitation between the years 1985

<sup>4</sup> <http://www.iaea.org/water> (07.01.2014).

and 2005 are available and give a good impression of seasonal variability. The long-term weighted mean is  $-7.1\text{‰}$  for Koblenz and  $-7.9\text{‰}$  for Karlsruhe. It can be expected that the modern  $\delta^{18}\text{O}$  value of precipitation for the Upper Rhine Valley in the area around Worms is within this range. When comparing the different oxygen isotope values between the years 1981 to 2005, it can be detected that there is a variation of around  $3\text{‰}$  between single years. In Koblenz, the range of the documented annual average  $\delta^{18}\text{O}$  values between the years 1981 and 2005 is between  $-5.7\text{‰}$  and  $-8.7\text{‰}$  with a difference between the minimum and maximum mean value of  $-3\text{‰}$ . The seasonal variation is clearly visible with the highest value of  $-4.6\text{‰}$  in July and the lowest in December with  $-9.9\text{‰}$ . For Karlsruhe, the range varies from  $-6.7\text{‰}$   $\delta^{18}\text{O}$  to  $-9.4\text{‰}$   $\delta^{18}\text{O}$  with a difference of  $-2.7\text{‰}$ . The highest value is  $-5.4\text{‰}$   $\delta^{18}\text{O}$  in July and the lowest in December with  $-10.1\text{‰}$ . When considering the data collection from Stuttgart it is clearly visible that there is a decreasing tendency of  $\delta^{18}\text{O}$  values from northwest to southeast (Fig. 3.4).

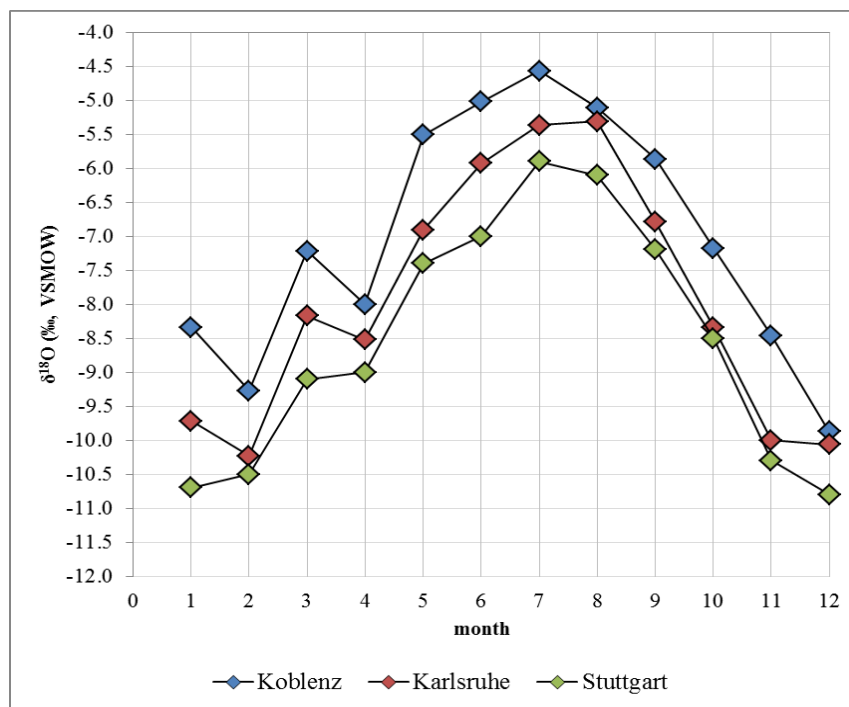


Fig. 3.4. GNIP  $\delta^{18}\text{O}$  values Koblenz, Karlsruhe and Stuttgart (data from IAEA/WMO 2006).

The second database which is often used to obtain local  $\delta^{18}\text{O}$  values is the OIPC (The Online Isotopes in Precipitation Calculator)<sup>5</sup> that uses measured  $\delta^{18}\text{O}$  data from different weather stations and interpolates them. The results are additionally

<sup>5</sup> [http://wateriso.utah.edu/waterisotopes/pages/data\\_access/oipc.html](http://wateriso.utah.edu/waterisotopes/pages/data_access/oipc.html) (03.01.2014).

corrected for altitude (Bowen/Wilkinson 2002; Bowen/Revenaugh 2003; Bowen et al. 2005; West et al. 2010). These data are only effective when they are applied at the appropriate geographic resolution. They are insufficient on a local scale and can lead to incorrect estimates when attempting to determine the exact isotopic composition of meteoric waters at a given site. Predicted annual  $\delta^{18}\text{O}_{\text{VSMOW}}$  values for the sites under study in the northern Upper Rhine Valley are  $-8.0\text{‰}$  in Eppstein,  $-8.1\text{‰}$  in Dirmstein and  $-8.2\text{‰}$  in Bockenheim. The monthly range for all three sites is roughly between  $-10.5\text{‰}$  and  $-6\text{‰}$ . The same values ( $-8.1\text{‰}$ ) were also measured for Koblenz and Karlsruhe. This already shows that this tool is rather inappropriate for the evaluation of the local drinking water range.

Further  $\delta^{18}\text{O}_{\text{VSMOW}}$  values are available from the Rhine River (Buhl et al. 1991). Samples which are taken at the geographical height of the research area yielded low  $\delta^{18}\text{O}$  values of  $-9.8\text{‰}$  and  $-10.2\text{‰}$ . However, this source is not appropriate for the determination of the local oxygen range for several reasons. Rivers and streams contain different parts of  $\delta^{18}\text{O}$  from precipitation and from the water source depending on size and source area. Furthermore, the  $\delta^{18}\text{O}$  values vary in accordance with seasonality in response to local precipitation. The amplitudes are strongly dampened in comparisons to those of the precipitation water and there are only few per mille differences between the largest and the lowest values in river or stream waters as a result of a long-termed mixing of different precipitation events and ground water. In the Rhine River, variations mainly reflect Alpine snowmelt and to a lesser extent the actual precipitation events. Lowest  $\delta^{18}\text{O}$  values were measured during late spring and summer and not in winter as expected (Buhl et al. 1991). In addition, modern values of precipitation, surface and groundwater may deviate from values of the past.

Oxygen values of locally living humans in the same study region, preferably contemporary to the period under study, are certainly the best basis for comparison. Oxygen isotope signatures from archaeological material, especially human tooth enamel from sites of the Upper Rhine Valley, are more than rare. The only published oxygen isotope values are from a short report about human individuals of the Neolithic pit-enclosure Herxheim (Tütken et al. 2012). The oxygen isotopic composition from the phosphate fraction ( $\delta^{18}\text{O}_{\text{pVSMOW}}$ ) of human tooth enamel of more than 45 individuals was measured. In many cases, several teeth per individual were analysed. The total variation of the oxygen isotope of all samples was more than

5‰. The largest variability was found between first molars (15.7 to 20.2‰;  $n = 43$ ), followed by second molars (15.4 to 19.0‰,  $n = 19$ ) and the lowest variation in the third molars (16.0 to 18.0‰,  $n = 25$ ). As the first molar may be enriched by breast milk, the local drinking water signature was calculated only with later forming teeth. The  $\delta^{18}\text{O}_{\text{mw}}$  range calculated with the equation from Daux (Daux et al. 2008) showed a range between  $-10$  to  $-6$ ‰, spanning the complete range for precipitation  $\delta^{18}\text{O}$  values in Central Europe. Based on an oxygen value of  $-8$ ‰, which was probably calculated with the OIPC and a deviation of  $\pm 1$ ‰ within human communities, the local drinking water range for Herxheim was defined between  $-9.2$ ‰ and  $-7.2$ ‰ (Tütken et al. 2012, 95–98). Unfortunately, the described data is from a short report with no detailed information, the complete data set is not published yet.

Further investigations of oxygen isotope signatures of skeletal material from the northern Upper Rhine Valley are only available from animal remains. Faunal  $\delta^{18}\text{O}$  values cannot be directly compared with those of humans because of differences in diet, metabolism and food processing and only provide a general idea of the oxygen isotope signature of an area. Oxygen isotope measurements from the phosphate fraction ( $\delta^{18}\text{O}_{\text{pVSMOW}}$ ) were conducted on a second molar and bone sample of the early medieval equid from Frankenthal (Tütken et al. 2004). The  $\delta^{18}\text{O}_{\text{pVSMOW}}$  values for the bone samples are 17.5‰ in the central part and 17.0‰ in the outer part of the cortex. The tooth enamel had a  $\delta^{18}\text{O}_{\text{pVSMOW}}$  value of 17.0‰. The results are seen as authentic signals because of the good accordance between the values of both elements. The conversion of the results in drinking water values shows a range between  $-6.6$  to  $-7.2$ ‰  $\pm 0.4$ ‰ and it was concluded that the equid imbibed water during his life from lowland regions in western or northwestern Germany. It is excluded that the animal drank water from the Rhine, which has  $\delta^{18}\text{O}$  values around  $-11.0 \pm 1.5$ ‰ ( $\delta^{18}\text{O}_{\text{pVSMOW}} \sim 15$ ‰), or from upland regions with also lower  $\delta^{18}\text{O}$  values (Tütken et al. 2004, 101–103). Pleistocene mammals from Rhine gravel deposits showed lower  $^{18}\text{O}_{\text{pVSMOW}}$  values between 15 and 16‰ which is interpreted as the reflection of climatic conditions during a glacial period. Horse remains, which were also found in Rhine gravel deposits, have the same  $^{18}\text{O}_{\text{pVSMOW}}$  range as the medieval mammal. It is supposed that they are the remains from an interstadial period or also from the Holocene Interglacial (Tütken et al. 2004, 103).

Oxygen and carbon isotope values were also analysed from three Neolithic pigs from Goddelau. The isotopes were measured against the VSMOW standard in

the structural carbonate of tooth enamel from the third molars and have  $\delta^{18}\text{O}$  values of  $24.47 \pm 0.03\text{‰}$ ,  $26.08 \pm 0.03\text{‰}$ , and  $23.39 \pm 0.05\text{‰}$  (Bentley/Knipper 2005, 635, Tab. 1). The  $\delta^{18}\text{O}$  value of  $26.08 \pm 0.03\text{‰}$  is seen as untypical for the region and interpreted as imported animal. The average value for the local sample is  $23.9 \pm 0.8\text{‰}$  ( $\delta^{18}\text{O}_{\text{CVSMOW}}$ ). By using the regression equation from Longinelli (1984) they calculated a local meteoric water value of  $-11.2 \pm 0.8\text{‰}$  (Bentley/Knipper 2005, 635).

Only these few examples still show the problems which are connected with the comparison of  $\delta^{18}\text{O}$  values between sites, different periods, species, labs, equations, material (carbonate, phosphate), standards, etc. Furthermore, oxygen values of precipitation do not only vary between seasons, but also between different years, the type of drinking water and also the cultural habitats for processing water in food and drink. Therefore, the best way to define the local range is to do it with the produced data itself.

### *3.1.2.3 Carbon isotope signatures*

In early medieval temperate Europe, the majority of plants use the  $\text{C}_3$  pathway. Broomcorn and foxtail millet are the only known domesticated  $\text{C}_4$  plants. Millet has been cultivated in Europe since the Neolithic and was used as a staple food during prehistory (Schmidl et al. 2007; Hunt et al. 2008). The importance of millet in diet is difficult to determine because it is underrepresented in archaeobotanical material, but can occur in large amount in waterlogged contexts (Rösch et al. 1992). Archaeobotanical investigations of early medieval sites are rare, but a study of sites in Southwest Germany indicates that broomcorn and foxtail millet could be identified at 10 and 30% (Rösch 1998; Rösch 2008). There are no studies available which measured carbon isotope values of the structural carbonate of human tooth enamel from contemporary sites in the northern Upper Rhine area. The nearest early medieval site is Wenigumstadt in northern Bavaria around 80 km northeast of the research area. The 182 analysed enamel samples showed  $\delta^{13}\text{C}_{\text{CVPDB}}$  values between  $-15.2$  and  $-12.0\text{‰}$  with a mean of  $-13.7 \pm 0.6\text{‰}$ . When only individuals were included that are determined to be local based on the strontium isotope analyses the range measured between  $-15.2$  and  $-12.7\text{‰}$  with a mean of  $-13.8 \pm 0.6\text{‰}$  (Vohberger 2011, 120). These  $\delta^{13}\text{C}$  values are typical for a  $\text{C}_3$  based terrestrial diet in Central Europe, which is also known from other contemporary sites in Germany, based on  $\delta^{13}\text{C}$  analyses of bone collagen (Schutkowski et al. 1999; McGlynn 2007; Hakenbeck et al. 2010;

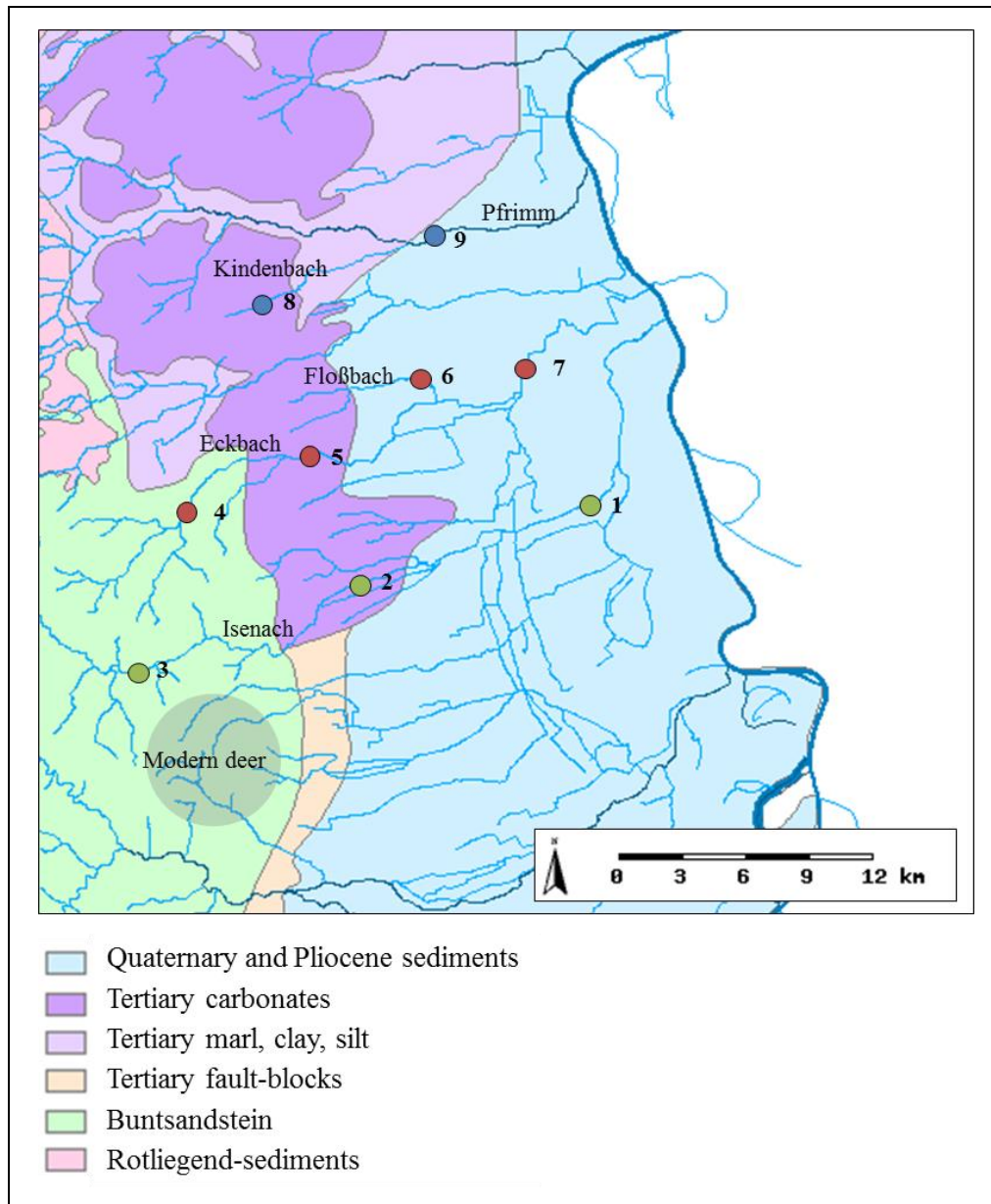
Hakenbeck et al. 2012; Vohberger 2011; Knipper et al. 2012b). Furthermore, these investigations revealed rather narrow  $\delta^{13}\text{C}$  ranges with low standard deviations, indicating rather homogeneous diets. Variations resulted primarily due to the consumption of  $\text{C}_4$  plants, such as millet, by few individuals (Hakenbeck et al. 2010; Schutkowski et al. 1999) or as a reflection of environmental variation in an Alpine environment (McGlynn 2007).

### 3.1.3 Samples for the local strontium range

#### 3.1.3.1 Water samples

In order to get a better understanding of the distribution of  $^{87}\text{Sr}/^{86}\text{Sr}$  in the western tributaries of the Rhine River, which flow through the research area, a total of nine water samples were collected during August 2012 (Fig. 3.5). The samples were taken from the streams that run through the sites under study. In general, the aim was to collect samples at regular intervals beginning at the spring and further towards each site, especially at the location of each cemetery. The first site, Bockenheim, is situated near the small stream Kindenbach, which rises only few km west of Bockenheim between Biedesheim and Kindenheim and enters the Pfrimm River, a tributary of the Rhine, to the east. The first sample (no. 8) was taken between Kindenheim and Bockenheim in an area belonging to the hydrological landscapes of Tertiary carbonates of the Mainz Basin. The second sample was taken at the location where the Kindenbach stream enters the Pfrimm River (no. 9). This site already belongs to the area with Quaternary and Pliocene sediments. Both streams transverse mainly modern agricultural areas. The second site of this study, Dirmstein, is situated at the interface of two streams, the Eckbach in the south and Floßbach in the north. The Eckbach rises in the Buntsandstein area of the Palatinate Forest. Three samples were taken from this stream, the first (no. 4) in the Buntsandstein area in the forest, the second (no. 5) in Kirchheim situated on Tertiary carbonates and the last (no. 7) shortly after Dirmstein on Quaternary-Pliocene sediments. All three sampling locations are situated in anthropogenic-influenced territory. Especially the last two sites transverse modern agricultural areas. Another sample (no. 6) is taken from the Floßbach stream in the vicinity of the site itself which rises out of several spring streams on Tertiary carbonates and enters the Eckbach at Dirmstein. Eppstein, the most southern site, lies at the Isenach stream, a main tributary of the Rhine. A total of three samples were

taken. The first sample (no. 3) was collected near the Isenachweiher in the Palatinate Forest in the Buntsandstein area. This sampling location was most probably not anthropogenically influenced. The second sample (no. 2) was taken near Ungstein on Tertiary sediments and the last sample near Eppstein, on Quaternary-Pliocene sediments (no. 1). The Isenach is one of the most anthropogenically polluted tributaries of the Rhine River in Rhineland-Palatinate.



**Fig. 3.5. Sampling location of water and deer samples (map: Geoexplorer of the Rhineland-Palatinate Water Management<sup>6</sup>).**

<sup>6</sup> [http://www.geoexplorer-wasser.rlp.de/geoexplorer/application/geoportal/geoexplorer.jsp?property\\_name=geoportal](http://www.geoexplorer-wasser.rlp.de/geoexplorer/application/geoportal/geoexplorer.jsp?property_name=geoportal) (10.01.2014).



### 3.1.3.2 *Modern deer samples*

As reference values for the Buntsandstein area of the Palatinate Forest are lacking, tooth enamel of three modern deer were analysed. The animals were culled in 2011 in the area around the Drachenfels in the Palatinate Forest (Fig. 3.5). The lower jaws were kindly provided by the forestry commission office of Bad Dürkheim. The animals were not fed, but it cannot be excluded that they obtained food from fields or vineyards in the Upper Rhine Valley. Dental enamel from the M2 of each lower jaw was collected and analysed.

### 3.1.3.3 *Further samples*

In order to characterise the local strontium range of each site, several archaeological samples, such as animal tooth enamel, human and faunal dentine as well as eggshells and soil samples, were collected. The details are outlined in the “Samples and sampling strategy” part of each site in the following section.

## 3.2 Eppstein

### 3.2.1 Location and natural conditions

Eppstein, a district of the town Frankenthal/Palatinate, is situated in the Anterior Palatinate in the Upper Rhine Valley in Rhineland-Palatinate. Worms is located around 15 km to the north and Speyer 25 km to the south. 15 km to the east are the Haardt Mountains, and the Rhine lies 7 km to the east. During the Early Medieval period, the Rhine was only 2–3 km from the village. Eppstein is situated on the Frankenthaler Terrace, which is a 1.5 km broad plain area extending parallel to the Rhine between Speyer and Worms at an altitude of 95 to 100 m NHN. To the east, the area is separated from the Rhine depression by a fluvial terrace. To the west, the terrace is delimited to the loess plateaus by a 2–10 m high increase of the terrain (Weidenfeller/Kärcher 2008). The Frankenthaler Terrace is comprised of Quaternary fluvial deposits and a 5–10 m thick layer of gravel and sand (for a geological map see Fig. 10.1)<sup>7</sup>. The main substrates of the soil (fertile luvisol and chernozem) are sandy deposits which are covered by flooding clay. The western part of the terrace is strongly influenced by groundwater resulting in very moist soil such as gley and

<sup>7</sup> <http://www.luwg.rlp.de/Aufgaben/Naturschutz/Grundlagendaten/Naturraeumliche-Gliederung/Naturraeumliche-Gliederung-von-Rheinland-Pfalz/> (13.12.1013).

alluvial soils<sup>8</sup>. The average temperature is 9–10 °C and the average annual rainfall is ca. 500–550 mm<sup>9</sup>. To the north of Eppstein flows the Isenach, a 36 km long stream which rises in the Palatinate Forest 2 km southwest of Carlsberg-Hertlinghausen and flows into the Rhine around 4 km south of Worms near Bobenheim-Roxheim. The Isenach is one of the most anthropogenically polluted streams in Rhineland-Palatinate.

### 3.2.2 Research history

The early medieval cemetery was situated on the southeastern fringe of the village of Eppstein at a height of approximately 95 m NHN (Polenz 1988, 133; Engels 2012, 11). First findings were made in the 1870s during sand mining. The site is one of the longest known early medieval cemeteries in the Palatinate region (Engels 2012, 11). Smaller excavations were conducted at the beginning of the 20<sup>th</sup> century as well as in 1967 (Polenz 1988, 133–135; Engels 2012, 11). The archaeological remains, which were excavated until 1967, were published by H. Polenz (Polenz 1988, 133–146). Between 1983 and 1988, a large excavation of the site was realised which included almost the complete burial area with an expanse of 142 m north-south and 96 m west-east. A total of 447 graves were detected (Engels 2012, 11–13). The remains of this new excavation were investigated in a dissertation by C. Engels (Engels 2012). Together with stray finds and the ca. 41 graves which were detected until 1967 and an unknown number of destroyed or undetected graves, it is supposed that the graves totaled between 500 and 550 in number (Engels 2012, 14). Only the skeletons of the modern excavation were anthropologically investigated. The used sex and age determinations were extracted from Engels' catalogue. The cemetery is not only the oldest known but also the most completely excavated burial place of the region. The evaluation revealed that Eppstein was continuously in use from the last third of the 5<sup>th</sup> century to the end of the 7<sup>th</sup> century. Furthermore, Eppstein is one of the few cemeteries on the western side of the northern Upper Rhine Valley that yielded a relatively large amount of burials of the last third of the 5<sup>th</sup> century (Engels 2012, 219–220).

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<sup>8</sup> [http://mapserver.lgb-rlp.de/php\\_bfd200/index.phtml](http://mapserver.lgb-rlp.de/php_bfd200/index.phtml) (23.12.2013).

<sup>9</sup> [http://mapserver.lgb-rlp.de/php\\_guek/index.phtml](http://mapserver.lgb-rlp.de/php_guek/index.phtml) (23.12.2013).

The archaeological remains of the associated settlement have not been detected yet. The village name Eppstein is composed of the fundamental word *-stein* and the name Abbo/Appo/Ebbo, which is the abbreviation of the name Eberhard, and means probably that the place was the property of a person named Eberhard. The fundamental word *-stein* belongs to the oldest charge of places, which are already documented in the 8<sup>th</sup> century, and it is supposed that the word refers to a Roman stone building or the remains of such a house (Engels 2012, 24; Staab 1975, 118–119). Indeed, Roman stray finds have been found in the vicinity of the early medieval cemetery, indicating the presence of a Roman settlement (Engels 2012, 24). Furthermore, it was reported that the fundamentals of a house in Eppstein were comprised of very old and thick stones which may be the remains of a Roman building (Engels 2012, 25). It is also known from other places with the fundamental word *-stein*, which were built before high medieval castle structures, that remains of Roman buildings or fortifications were detected, for example, at Ungstein or Zullenstein (Engels 2012, 24). The first documented evidence of Eppstein is from a copy of the *Codex Laureshamensis* and dates to the 30<sup>th</sup> of March, 769 (Engels 2012, 25).

### 3.2.3 Occupation history and interpretation

The oldest founder graves are situated as a closed group in the southeast section of the cemetery and date to the last third of the 5<sup>th</sup> century, SD-phase 2–3. A total of ten graves are assigned to these phases (SD-phase 2: grave 45, 52, 67C, 275, 280?, 396, 399?; SD-phase 2–3: grave 50, 66?; SD-phase 3: grave 83) (Engels 2012, 198). As a result of the heavy plundering of the graves, whereas most of the good datable metal objects were lost, it is difficult to assign these graves to a certain SD-phase with safety (Engels 2012, 198). Typical finds are combs with three layers and rectangular handle strips, kidney-shaped buckles without fittings, and zoomorphic brooches. Typical are also jugs and pots which are mainly younger variants of late Roman types. The graves are small and arranged simply, sometimes with a real *Totenbrett* or an organic underlayment. In one case, a niche grave has been detected (Engels 2012, 198). Based on the anthropological investigations, this group consist of at least juvenile male and female individuals. No graves of children have been detected. All individuals were equipped with grave offerings and costume accessories. After the quality model of

Christlein (Christlein 1973), six individuals belong to the quality group A, two to B1 and two to B2. However, this has to be taken with caution as all graves were plundered and probably originally had more grave goods, especially metal objects which were the main target of the robbers. The still existing grave goods of the founder graves show influences from several cultural areas. Special ceramic vessels, so-called *Rillenbecher*, are common for Southwest Germany, the Alemannic area. A special brooch and a hand-made vessel are typical for an “Elbe-Germanic”-Thuringian cultural milieu in the region of Middle Germany. Furthermore, some objects of the female jewellery are positioned in a Roman/Mediterranean cultural context. Based on these mixed traits, the founder group was characterised as “polyethnic” or “multicultural” (Engels 2012, 210–212). As the archaeological research has shown that Roman structures in the region were still existent in the second half of the 5<sup>th</sup> century, it is assumed that remaining late Roman communities had a strong influence on the foundation of this cemetery. The Alemannic influences are rather interpreted as diffusion phenomenon of two adjacent regions than the larger immigration of people from Southwest Germany. In contrast, the “Elbe-Germanic”-Thuringian influences are interpreted as the first immigration from Middle Germany already at that time and not only after the beginning of the Merovingian influence in the region, as commonly assumed (Engels 2005a, 327–331, Engels 2012, 210–212). The lack of graves which can be assigned to SD-phase 3 is not a hiatus in the occupation of the cemetery, but is rather the result of the poor dating of the remaining objects. Arguments for continuity between SD-phases 2–3 and 4 include observations on the spatial distribution of the graves, which does not show a break, and a secondary burial in a grave of the founder period (Engels 2012, 198).

Around 22 graves can be dated to SD-phases 4 and 4–5 (SD-phase 4 = 12; SD-phase 4–5: 10) (Engels 2012, 198). Most of the graves were destroyed and plundered so that good datable objects are rare. Only two graves (grave 35 and 439) can be assigned to quality group B after Christlein. The graves are situated west of the founder graves in direct association and extend the burial place towards the west and north (Engels 2012, 198). A special kind of wheel-made pottery (*Knickwandtöpfe mit einschwingender Oberwand*) is connected with the Merovingian influence in this region. Hand-made pottery with “Elbe-Germanic”-Thuringian influence from the graves 35, 428 and 433 and observations about the form and position of spearheads in the graves 35, 38 and 426B is interpreted as evidence for the immigration of

individuals from Middle Germany. As these influences were also detected in the founder graves, this is not seen as a new immigration resulting from a controlled settlement process by the Merovingian kings but rather as a sign of continuity since the 5<sup>th</sup> century (Engels 2005a, 329–331; Engels 2012, 198; 211–212).

At least 22 graves can be assigned to SD-phase 5. When including those of SD-phases 4–5 and 5–6, the number increases to around 38 (SD-phase 4–5: 10; SD-phase 5–6: 6) (Engels 2012, 198–200). In the middle of the 6<sup>th</sup> century, the typical Frankish funeral tradition was completely developed and the burial place is a typical row-grave cemetery, which can be identified by the ordering of the graves. The burial site is extended to the west where it reaches a straight border. At this time numerous new cemeteries were founded in the Upper Rhine Valley, which is considered as a “colonisation” of new land mainly by newcomers. For the first time, three quality stages can be divided. Burials of the group C (graves 46, 211?) and B (graves 192, 208, 222, 423, and 410) are mainly located in the core area of the cemetery. Rich graves have broad rectangular chambers. Some grave goods show that objects were already obtained from western areas or that there were personal contacts to these areas. Some graves contained hand-made pottery in “North Sea Germanic” tradition (graves 189, 192, 423). After Engels, this is a proof that “Frankish colonisation” was only possible with the help of non-Frankish barbarian people. Furthermore, he argues that the amount of similar pottery, which has been found in other sites of the area, are too numerous to explain their appearance with the mechanism of exogamy (Engels 2012, 200–201).

At least approximately 39 graves can be assigned to SD-phase 6. The number increases to 56 when those of the SD-phases 5–6 and 6–7 are included (SD-phase 4–5: 6; SD-phase 6–7: 11) (Engels 2012, 200). The burials of this time period were placed in the old burial area but also towards new areas in the north. The burials of the southern areas are rich and consist of large chamber graves (graves 211, 188, 409, 193) and graves of the quality group B (graves 55, 405, 226, 422, 435). The northern area is characterised by large and elaborate grave constructions. The continuance of the row-graves is visible for several generations. Particularly notable are the burial mounds which are circumvented by a circular ditch of the quality groups C and B2 (graves 162 and 169).

### 3.2.4 Research questions

The main aim of the multi-isotopic study of human tooth enamel from individuals of the cemetery Eppstein is to detect local and non-local individuals. Furthermore, it will be investigated, how patterns of mobility changed between the late 5<sup>th</sup> and the 6<sup>th</sup> century during the time after the end of the Western Roman Empire and the emergence of the consolidation of the Merovingian power. The following research questions will be pursued:

- Was the foundation of the cemetery in the late 5<sup>th</sup> century connected to the immigration of newcomers?
- Which role did the former late Roman community play in the foundation of this cemetery?
- Is the “multicultural” character of the founder graves also visible in the isotopic data?
- How probable is the immigration from regions of Middle Germany and/or Southwest Germany in the late 5<sup>th</sup> and early 6<sup>th</sup> century as indicated by the grave goods? Which areas can be excluded as regions of origin?
- Is there continuity between the founder graves of the late 5<sup>th</sup> and the graves of the early 6<sup>th</sup> century as indicated by the occupation of the cemetery?
- Was there immigration from the North Sea area in the middle of the 6<sup>th</sup> century as indicated by hand-made pottery? Is it possible to detect immigrants from this area? Are there immigrants from other areas?
- Do the rich graves with burial mounds of the 6<sup>th</sup> century reflect the establishment of a local elite? Or is this connected to mobile elites?
- How dynamic was the rate of mobility? Are there differences between the time periods?
- Can we connect the developments in the rural community with main political events of this time? What new insights can we detect behind the archaeological and historical hypotheses?
- Who was more mobile? Are there differences concerning sex, age or social groups?
- To what extent do foreign grave goods reflect a foreign origin? Are there other reasons for the placing of “foreign” objects?

### 3.2.5 Samples and sampling strategy

#### 3.2.5.1 Human samples

The aim of sampling was to collect a representative number of individuals from each SD-phase from the beginning of the cemetery in the late 5<sup>th</sup> century to the late 6<sup>th</sup> century. A total of 65 teeth from 65 individuals were sampled. If possible, the M2 was collected in order to avoid a breastfeeding signal. If this was not possible, another tooth was chosen in the order of preference P2, P1, M3, M1, C, I. From the earliest graves (SD-phase 2–3), a total of eight out of ten individuals could be sampled. From SD-phases 4/4–5, 11 individuals and from SD-phases 5/5–6 14 individuals were sampled. A total of 31 individuals were collected from SD-phases 6/6–7. One sample dates to the SD-phases 3-5 (Tab. 3.1).

**Tab. 3.1. Human samples from Eppstein (sorted by SD-phase).**

(F/F? = female/probable female; M/M? = male/probable male; ND = not determined; ? = contradicting determinations; italicised = own observations concerning age; arc = sex based on grave goods, ant = sex based on osteological investigation; \* = definition of age groups - child: infans I, infans II; young adult: juvenile, adult I; adult: adult II, mature I; old adult: mature II, senile)

Grave	Tooth	SD-phase	Quality	Sex arc/ant	Sex	Age	Age group*	Destruction
52	M1?	2	A?	M?/ND	M?	Nd ( <i>at least adult</i> )	Adult	Yes
67C	M2?	2	B2	F/F	F	Adult I	Young adult	Yes
275	M3?	2	A?	ND/ND	ND	Nd ( <i>at least adult</i> )	Adult	Yes
396	M2	2	A?	ND/M	M	Juvenile	Young adult	Yes
280	P2	2?	B1	F?(F)	F?	Nd ( <i>at least adult</i> )	Adult	Yes
50	M3?	2-3	A1	ND/ND	ND	Nd ( <i>at least adult</i> )	Adult	No
66	M2?	2-3?	A?	ND/ND	ND	Nd ( <i>at least adult</i> )	Young adult	Yes
83	M2	3	B2	F/F	F	Adult I	Young adult	Yes
35	M2	4	B2	M/M	M	Adult	Adult	No
48	M2	4	A1	M/(M)	M	Adult I	Young adult	Yes
433	M2	4	A1	F/F	F	Adult I	Young adult	Yes
49	M2	4?	A1	M?/(M)	M?	Adult	Adult	No
425	M2	4?	A2	M/M	M	Juvenile	Young adult	No
431	P1	4?	A?	F/F	F	Nd ( <i>at least adult</i> )	Adult	Yes
437	M2	4?	A2	M/M	M	Adult I	Young adult	No
436	M2	4-5	A1	M/M	M	Senile	Old adult	No
37	M2	4-5?	A?	ND/M	M	Adult I	Young adult	Yes
47	M2	4-5?	A1	M?/ND	M?	Nd ( <i>at least adult</i> )	Adult	No
58	P2	4-5?	A1?	M?/F	?	Nd ( <i>at least adult</i> )	Adult	Yes
38	M2	5	A1	M/ND	M	Nd ( <i>at least adult</i> )	Adult	No
46	M2	5	C	M/ND	M	(Juvenile)	Young adult	Yes
111	M2	5	A1	M/M	M	Adult I	Young adult	Yes
189	M1	5	A1	F?/M	?	Infans II	Child	Yes
192	M1	5	B2	F?(F)	F?	Infans I	Child	Yes
222	P1	5	B1	M/ND	M	Nd ( <i>at least adult</i> )	Adult	Yes

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411	M1	5	A1	F/ND	F	Nd (child)	Child	No
418	M2?	5	A2	F?/ND	F?	Nd ( <i>at least adult</i> )	<i>Adult</i>	Yes
67A	C?	5?	A1	F/F	F	Mature II	Old adult	Yes
413	M2	5?	A2	F/F	F	Adult I	Young adult	Yes
426B	P2	5?	A1	M/M	M	Adult I	Young adult	Yes
62	M2	5-6	A1	M/M	M	Juvenile	Young adult	Yes
208	M2	5-6	B1	ND/ND	ND	Nd ( <i>at least adult</i> )	<i>Adult</i>	Yes
211	P1	5(-6)	C	F?/(M)	?	Adult II	Adult	Yes
428	m1?	3-5?	A1	ND/ND	ND	Nd (child)	Child	No
29	M	6	A2	F/F	F	Nd ( <i>at least adult</i> )	<i>Adult</i>	Yes
30	P	6	A1	F/F	F	Mature II	Old adult	Yes
55	P2	6	B2	F/F	F	Adult	Adult	No
61	M2	6	A?	ND/(F)	F?	Nd ( <i>at least adult</i> )	<i>Adult</i>	Yes
70	M1?	6	B2	F/F	F	Senile	Old Adult	Yes
162	M2	6	B2	M/M	M	Adult I	Young adult	Yes
167	P2	6	A2	F?/(M)	?	Adult I	Young adult	Yes
168	M1	6	B1	M/ND	M	Nd (child)	Child	Yes
182	M1	6	A1	M/M	M	Infans II	Child	No
197	M2?	6	A1	F/F	F	Juvenile	Young adult	Yes
198	M2	6	A?	ND/F	F	Adult I	Young adult	Yes
217	M1?	6	A2	F/ND	F	Nd (child)	Child	No
224	m1	6	A1	M/ND	M	Nd (child)	Child	Yes
226	M2	6	B1	F/ND	F	Nd ( <i>at least adult</i> )	<i>Adult</i>	Yes
228	M2	6	A1	F/F	F	Juvenile	Young adult	Yes
246	M2	6	B1	M/M	M	Adult II	Adult	Yes
279	M	6	A2	M/M	M	Mature I	Adult	Yes
391	P?	6	A2	M/M	M	Nd ( <i>at least adult</i> )	<i>Adult</i>	Yes
405	M2	6	B2	M/M	M	Senile	Old adult	Yes
421	P?	6	A?	F/F	F	Nd ( <i>at least adult</i> )	<i>Adult</i>	Yes
422	M1	6	B1	M/ND	M	Nd (child)	Child	Yes
435	M1	6	B1	F/ND	F	Nd (child)	Child	No
71	M2	6/7?	A?	ND/M	M	Mature II	Old adult	Yes
25	M2	6?	A1	M/M	M	Infans II	Child	No
39	M2	6?	A1?	ND/F	F	Senile	Old adult	Yes
188	M2?	6?	A?	F/F	F	Adult	Adult	Yes
3	M2	6-7	B1	M/M	M	Adult	Adult	Yes
4C	M2	6-7	A2	F/F	F	Juvenile	Young adult	Yes
74	M2	6-7	B1	M?/M	M	Adult	Adult	Yes
233	P2	6-7	B2	M/M	M	Mature	Adult	Yes
245	M1	6-7	A?	ND/ND	ND	Nd (child)	Child	Yes

### 3.2.5.2 Samples for the local strontium range

For the determination of the biologically available strontium signature at the site of Eppstein, bulk samples of faunal tooth enamel and dentine samples, eggshells, as well as human dentine samples and a soil sample were collected (Tab. 3.2). The faunal



teeth include samples from two cattle, three pigs, one sheep/goat and one horse. The animal teeth were all sourced to the grave infillings, but it is unclear if these grave infillings, and consequently the bone specimens, date to an early medieval context. A total of three samples were taken from this tooth for strontium isotope analysis. These include one homogenised bulk sample, as well as one sample from the tip and the other from the cervix of the tooth. The pig tooth from grave 249 was also found in the grave infilling. The grave was undestroyed and contained bones from pig, cattle and sheep/goat as food offerings. The last sampled pig tooth is from the destroyed chamber grave 11 and was extracted from a pig skull. The teeth from a cattle and a sheep/goat of grave 358 were also found in the grave infilling and were probably not part of a food offering. Three samples were taken from the cattle tooth for the strontium isotope analyses. The first was a bulk sample; the second was taken at the tip and the last at the cervix of the tooth. The cattle tooth from grave 269 is also from the infilling but was only sampled as bulk. The horse tooth belonged to a complete horse skeleton which was buried in a separate pit dating to the Early Middle Ages. The eggshells were all deposited in the graves as food offerings. The taxonomic identification was performed with a highly sensitive mass spectrometry and the peptide mass fingerprinting (ZooMS) method by John Stewart (Stewart et al. 2013). The identification of faunal bone and teeth material was conducted by Anja Prust. The human and faunal dentine samples were randomly collected. The analysed soil sample was from material which was attached to a bone.

**Tab. 3.2. Samples for the determination of the local strontium range at Eppstein.**

Grave	Material	Species	Tooth	Date	Context
269	Enamel	Cattle	P	?	Single tooth, stray find
358	Enamel	Cattle	M1	?	Single tooth, stray find
11	Enamel	Pig	M	Early medieval	Grave offering (pig skull)
249	Enamel	Pig	M3	?	Single tooth, stray find
270	Enamel	Pig	I	?	Single tooth, stray find
358	Enamel	Sheep/goat	M2	?	Single tooth, stray find
15	Enamel	Horse	M	Early medieval	Horse burial
217	Eggshell	Domestic chicken	-	Early medieval	Food offering
222	Eggshell	Anseriform (duck/goose)	-	Early medieval	Food offering
236	Eggshell	Domestic chicken	-	Early medieval	Food offering
255	Eggshell	Anseriform (duck/goose)	-	Early medieval	Food offering
292	Eggshell	Domestic chicken	-	Early medieval	Food offering
411	Eggshell	Domestic chicken	-	Early medieval	Food offering
422	Eggshell	Domestic chicken	-	Early medieval	Food offering
358	Dentine	Cattle	M1	?	Single tooth, stray find

249	Dentine	Pig	M3	?	Single tooth, stray find
270	Dentine	Pig	I	?	Single tooth, stray find
15	Dentine	Horse	M	Early medieval	Horse burial
3	Dentine	Human	M2	Early medieval	Burial
38	Dentine	Human	M2	Early medieval	Burial
50	Dentine	Human	M(3?)	Early medieval	Burial
71	Dentine	Human	M2	Early medieval	Burial
189	Dentine	Human	M1	Early medieval	Burial
198	Dentine	Human	M2	Early medieval	Burial
246	Dentine	Human	M2	Early medieval	Burial
426B	Dentine	Human	P2	Early medieval	Burial
52	Soil	-	-	-	-

### 3.3 Bockenheim

#### 3.3.1 Location and natural condition

Bockenheim (district Bad-Dürkheim, Rhineland-Palatinate) is located in the Upper Rhine Valley in the northeast of the Palatinate region near the border to the Rhine Hesse region. The current village originally consisted of two localities, Großbockenheim in the south and Kleinbockenheim in the north, but they were joined in 1956. Bockenheim is situated at a level of around 160 m NHN in the southern part of the Rhenish-Hessian table and hill land at the sub natural division of the upper hill land of the Pfrimm River<sup>10</sup>. This is a gently undulating area situated at a height of around 120 to 160 m NHN on both sites of the Pfrimm River. The main part of the area is built of Tertiary deposits of the Mainz Basin covered with loess which can reach thicknesses of 12 to 15 m. In some areas, Tertiary layers (*Mergeltertiär*, *Kalktertiär*) are not covered by loess. The slopes of the streams are mainly comprised of limestone-marl material originating from the Tertiary deposits (geological map see Fig. 10.1)<sup>11</sup>. Soils around Bockenheim consist of colluvisols and lime chernozem which are comprised of loess. To the west of Bockenheim, pararendzina and colluvisols comprised of Tertiary clay marl are found<sup>12</sup>. The climate of the area is dry and warm. The average annual temperature is 9–10 °C and the average annual rainfall between 550 to 600 mm is less than measured in the Anterior Palatinate Upland<sup>13</sup>.

<sup>10</sup><http://www.luwg.rlp.de/Aufgaben/Naturschutz/Grundlagendaten/Naturraeumliche-Gliederung/Naturraeumliche-Gliederung-von-Rheinland-Pfalz/> (13.12.1013).

<sup>11</sup> [http://mapserver.lgb-rlp.de/php\\_guek/index.phtml](http://mapserver.lgb-rlp.de/php_guek/index.phtml) (23.12.2013).

<sup>12</sup> [http://mapserver.lgb-rlp.de/php\\_bfd200/index.phtml](http://mapserver.lgb-rlp.de/php_bfd200/index.phtml) (23.12.2013).

<sup>13</sup> <http://www.kwis-rlp.de/index.php?id=6867> (23.12.2013).

This is the result of the particularly pronounced lee situation in the northeast area of the Haardt Mountains. To the north of Bockenheim, in close vicinity of the cemetery, flows the Kindenbach. This is a nearly 10 km long tributary of the Pfrimm River which rises only few kilometres west of Bockenheim between Biedesheim and Kindenheim.

### **3.3.2 Research history**

Two early medieval cemeteries are known from Bockenheim. The graveyard Großbockenheim has been known since the end of the 19<sup>th</sup> century and was located at the western fringe of the village on a steadily in eastern direction sloping hill at a level of 175–180 m NHN. The few recovered findings were obtained from an unknown number of graves and can be dated to the 7<sup>th</sup> century (Polenz 1988, 63–65). No modern excavations were conducted. The cemetery in the area of Kleinbockenheim has also been known since the 19<sup>th</sup> century. It was located in the new residential area in the Heyer mead at a level of 182 m NHN on a steadily in western direction sloping hill. Only few finds from graves were found at the end of the 19<sup>th</sup> and the beginning of the 20<sup>th</sup> century (Polenz 1988, 65–66). Excavations were conducted between 1980 and 1991 by the former archaeological department of Speyer. A total of 583 burials were recovered and this is therefore the largest known early medieval cemetery in the northern Upper Rhine Valley to date (Polenz 1988, 65–66; Riemer 2008, 151). The site was not completely excavated, especially the border in the north and south were not reached. The archaeological preparation and evaluation of the finds and further evidence is still in progress and is conducted by E. Riemer. Only a few preliminary reports have been published (Bernhard 1997, 39–42 with further references; Riemer 2008, 151–154). The data for the anthropological determinations of age and sex were extracted from E. Riemer's preliminary catalogue. Although the graves were strongly plundered and destroyed, it is possible to date the occupation time of the cemetery. The oldest graves at the western edge of the cemetery are from the late 5<sup>th</sup> and early 6<sup>th</sup> century. An earlier establishment of the site is nonetheless possible because of its incomplete excavation. The site was probably used until the late 7<sup>th</sup> or early 8<sup>th</sup> century (Riemer 2008, 152). The settlement which probably belonged to the burial place has not been found, but it is supposed that it was in the vicinity of the old monastery. From written sources it is known that there was a place called Mittelhofen,

a royal residence of the 8<sup>th</sup> and 9<sup>th</sup> century (Riemer 2008, 152). The name Bockenheim or Buckenheim was first mentioned around 770 in the Lorscher Codex. The separation of Groß- and Kleinbockenheim was first mentioned in the 14<sup>th</sup> century (Riemer 2008, 152). The name is composed of two parts, the person name *Bucco* and the suffix *-heim*, meaning that this was the place of Bucco (Riemer 2008, 152). Relicts of a Roman villa rustica were found near the cemetery as well is in the vicinity of Kindenheim (Riemer 2008, 152; Bernhard 1997, 40).

### 3.3.3 Occupation history and interpretation

The archaeological evaluation of the cemetery of Bockenheim is not finished yet and therefore only very general statements about the settlement history and cultural interpretation can be made. In the southwestern part of the cemetery, the founder graves were detected which date to the late 5<sup>th</sup> and 6<sup>th</sup> centuries. One of the oldest graves, the burial of an older woman which was partly destroyed, had a glass vessel as a grave offering. Two other early graves hold burials of two women with precious grave goods. The young adult individual of grave 488 had a large bronze brooch (type Mainz-Bretzenheim after Kühn) which is otherwise also distributed in the Rhineland and Northern France (Bernhard 1997, 40). The grave equipment of the female adult individual of grave 482 was composed of pearls, earrings, a glass vessel, scissors, a clover-leaf jug, and a special brooch which was typical for the Frankish and Gothic area (Bernhard 1997, 40; Bernhard 1997, 44, Fig. 19). Similar grave goods were found with the female of grave 483 which could only be partly excavated (Riemer pers. comm.). The grave of the the adult woman (grave 486) dates around 500 and was equipped with a set of four brooches and a special silver arm ring (*Silberkolbenarmring*) (Bernhard 1997, 50; Riemer 2008, 153–154). Grave 389 of an older female individual dates to the first half of the 6<sup>th</sup> century (SD-phase 3–4) (Riemer pers. comm.) as well a girl who was buried with two small eagle brooches, two whorls, several beads and a ceramic beaker (*Knickwandbecher*) (Bernhard 1997, 40). Further graves of the densely occupied western part of the cemetery date between the late 5<sup>th</sup> and the 7<sup>th</sup> century (Riemer 2008, 152). Most of the grave goods are typical for the Frankish area, while graves with hand-made pottery are assumed to reflect the presence of immigrants during the 6<sup>th</sup> century, most probably from Middle Germany (graves 388, 400, 423, 545, 470, 392) (Riemer 2008, 154; Riemer pers.

comm.). A peculiarity of this cemetery is also the large amount of glass vessels, especially from the second and third part of the 6<sup>th</sup> century (Riemer 2008, 154). The special wealth of the community is also represented by two male graves (459 and 466) which were equipped with two berg crystal buckles dating to the second third of the 6<sup>th</sup> century. These buckles are rare in the region and are probably of Byzantine origin or were made in the eastern Mediterranean area. It is assumed that the individuals with the berg crystals may have temporarily served in the Byzantine army (Bernhard 1997; Riemer 2008, 153–154; Riemer pers. comm.). Other finds from female grave such as ivory rings, cypraea, sea snails from the Red Sea as well as beads made of amethyst and shell discs reflect the trading networks to the south (Riemer 2008, 154). The occupation of the cemetery becomes less dense when moving further to the northeast. At this part of the burial site, the first circular ditches with burial mounds and rich grave chambers from the 6<sup>th</sup> century were recovered (Bernhard 1997, 40). Further peculiarities include horse burials. In two cases, a pair of horses was buried in separate burial pits, including a horse without a head (Bernhard 1997, 41–42; Riemer 2008, 153). Several other circular pits from grave mounds dating to the 7<sup>th</sup> century may possibly reflect the beginning of the local elite (Riemer 2008, 153).

### **3.3.4 Research questions**

The cemetery of Bockenheim is, beside Eppstein, one of the few burial places in the Palatinate and Rhine Hesse region which yielded graves of the late 5<sup>th</sup> and the early 6<sup>th</sup> century. The archaeological evaluation of the data is not finished. However, preliminary information is detailed enough to make them comparable to the two other cemeteries under study. The following research questions will be investigated and compared with the results of the other cemeteries:

- Was the foundation of the cemetery connected to the immigration of newcomers?
- What role did the former late Roman community play in the foundation of this cemetery?
- How probable is immigration from regions of Middle Germany as indicated by hand-made pottery? Which areas can be excluded as regions of origin?
- Is there continuity between the founder graves of the late 5<sup>th</sup> and the graves of the early 6<sup>th</sup> century?

- How dynamic was the rate of mobility? Are there differences between the time periods? Are different immigration “waves” detectable?
- Who was more mobile? Are there differences concerning sex, age or social groups?
- To what extent do foreign grave goods reflect a foreign origin?

### 3.3.5 Samples and sampling strategy

#### 3.3.5.1 Human samples

Tooth samples were taken from a total of 30 individuals from the western part of the cemetery (Tab. 3.3). Only one tooth per individual was analysed. In order to avoid a breastfeeding signal only later forming teeth, if possible M2 or P2, were sampled. If both were not available, another tooth was chosen. From the earliest graves of the cemetery (SD-phase 2–3) it was possible to extract three samples from six datable individuals (graves 391, 482, and 488). It is assumed that more of these early graves are still existant in the unexcavated part of the cemetery. Two of the three not sampled individuals had no teeth and the skull of the third person was not excavated. From the first half of the 6<sup>th</sup> century (SD-phase 3–4, SD-phase 4–5, and SD-phase 5), a total of six individuals were sampled (graves 406, 424, 449, 454, 457, 486). 13 individuals were sampled from graves of the second half of the 6<sup>th</sup> century (graves 22, 382, 286, 395, 398, 421, 423, 459, 464, 466, 470, 478, and 492). For further eight individuals, it was just possible to roughly date them to the 6<sup>th</sup> century (graves 392, 396, 397, 461, 473, 474, 480, and 497). Other datable graves could not be sampled because no teeth were available or preservation was worse.

**Tab. 3.3. Human samples from Bockenheim (sorted by SD-phase).**

(F/F? = female/probable female; M/M? = male/probable male; ND = not determined; arc = sex based on grave goods, ant = sex based on osteological investigation; \* = definition of age groups - child: infans I, infans II; young adult: juvenile, adult I; adult: adult II, mature I; old adult: mature II, senile)

Grave	Tooth	SD-phase	Sex arc/ant	Sex	Age	Age group*
391	M <sub>2</sub> R	2-3	F?/ND	F?	Adult II	Adult
482	M <sup>2</sup>	3	F/F-M	F	Adult I –adult II	Adult
488	M <sub>2</sub> R	3	F/F	F	Juvenile-adult I	Young adult
449	M1	3-4	F/ND	F	Infans I	Child
486	M <sup>2</sup> L	3-4	F/F	F	Adult II-mature I	Adult
406	M <sub>2</sub> R	4-5	F/F	F	Senile	Old adult
457	M2?	4-5	M/M-F	M?	Juvenile-adult I	Young adult
424	M <sup>2</sup> L	5	F/F	F	Adult II-mature I	Adult

454	P <sub>2</sub> R	5	M/M-F	M?	Adult	Adult
464	M <sup>2</sup> R	5	M/F	?	Adult I	Young adult
22	M <sup>2</sup> L	5-6	M/M	M	Adult II	Adult
395	M <sub>2</sub> L	5-6	F/ND	F	Infans I	Child
423	M1	5-6	ND/ND	ND	Infans I	Child
459	M <sup>2</sup> R	6	M/M	M	Adult II-mature I	Adult
466	P <sub>2</sub> ?	6	M/M	M	Adult II-mature I	Adult
470	M <sup>2</sup> R	6	F/F	F	Juvenile-adult I	Young adult
392	M <sup>2</sup> L	4-7	F/F	F	Senile	Old adult
396	M <sup>2</sup>	4-7	F/ND	F	Infans II	Child
397	P <sub>2</sub> R	4-7	F/F	F	Adult I	Young adult
461	M1	4-7	ND/ND	ND	Infans	Child
474	M <sub>2</sub> R	4-7	F/F	F	Adult I-II	Adult
480	M1	4-7	M <sup>2</sup> /ND	M?	Infans I	Child
497	P <sub>2</sub> R	4-7	F/F-M	F?	Adult II-mature II	Adult
473	M1	5-7	F/ND	F	Infans I	Child
382	M <sup>2</sup> R	6-7	F/F	F	Mature II	Old adult
386	P <sub>1</sub> R	6-7	ND/ND	ND	Adult I-adult II	Adult
421	P <sub>2</sub> L	6-7	M/M	M	Adult I	Young adult
478	M2	6-7	F/ F-M	F?	Adult II-mature I	Adult
492	P <sub>2</sub> R	6-7	F/M-F	F?	Mature I-mature II	Old adult
398	P <sup>2</sup> R	7-8	M/M	M	Senile	Old adult

### 3.3.5.2 Samples for the local strontium range

For the determination of the biologically available strontium signature at the site of Bockenheim, bulk samples of faunal tooth enamel and dentine samples, eggshells, as well as human dentine samples and two soil samples were collected (Tab. 3.4). The faunal teeth include samples from cattle, pig, sheep/goat and dog. A total of four cattle teeth were sampled. These are single teeth from the graves 22, 181, and 195 as well as a tooth from a complete cattle jaw from grave 274. All teeth were found in the grave infillings of destroyed human burials, and cannot be assigned to the Early Medieval period with safety. The teeth from graves 181 and 195 were found close together and it is possible that they are from the same individuals. Two pig teeth were sampled. The tooth from grave 311 was extracted from a lower jaw of a destroyed early medieval grave that also contained prehistoric and Roman remains. The single incisor from grave 261 was found in the grave infilling of an early medieval grave together with remains of the grave goods but also prehistoric sherds. Both graves are located in the same burial area not far from each other and it cannot be excluded that they originate from a prehistoric context. The sampled sheep/goat tooth was from a pit

at the eastern end of the cemetery with two sheep/goat skeletons. The partial skeleton of a canid, from which a tooth was sampled, was found in the grave infilling. In this case it is also not known if this animal can be classified to an early medieval context. The sampled eggshells from the graves 342, 479, 451, 509 and 485 were placed as food offerings. The taxonomic identification was performed with a highly sensitive mass spectrometry and the peptide mass fingerprinting (ZooMS) method by John Stewart (Stewart et al. 2013). The identification of faunal bone and teeth material was conducted by Anja Prust. The human and faunal dentine samples were randomly collected. Soil samples from graves 135 and 181 were already taken during excavation.

### 3.3.5.3 Cattle samples for oxygen and carbon isotope analysis

Additionally, a total of three pairs of second and third molars from three cattle were sampled sequentially for oxygen and carbon isotope analysis. The samples are from the graves or pits 195, 181, 274 and 532. The teeth from the graves 195 and 181 probably belong to one individual. The temporal context of these samples is unclear. While the teeth from graves 195, 181, 274 may be categorised in a prehistoric temporal context, the teeth from grave 532 are rather from a more modern context because of the excellent preservation of the skeleton. The sequential sampling for oxygen and carbon isotope analyses was mainly performed in order to test the preparation technique. Furthermore, it is expected that the samples show a sinusoidal pattern reflecting seasonal variation within a year with increased values in summer and decreased values in winter. If the pattern is observed, this shows that the samples and therefore also indirectly most probably also the human teeth are not (strongly) diagenetically altered. In addition, the results provide a general overview about the seasonal variation of  $\delta^{18}\text{O}$  (and  $\delta^{13}\text{C}$ ) values in the northern Upper Rhine Valley, provided the animals obtained food locally from the Upper Rhine Valley which will be detected by analysing the  $^{87}\text{Sr}/^{86}\text{Sr}$  values.

**Tab. 3.4. Samples for the determination of the local strontium range at Bockenheim.**

Grave	Material	Species	Tooth	Date	Context
195	Enamel, dentine	Cattle	M2	?	Single tooth, stray find
181	Enamel, dentine	Cattle	M3	?	Single tooth, stray find
22	Enamel	Cattle	M2	?	Single tooth, stray find
274	Enamel, dentine	Cattle	M3	?	Complete jaw, stray find
311	Enamel	Pig	M3	?	Skull, grave floor
261	Enamel, dentine	Pig	I	?	Single tooth, stray find



533	Enamel	Sheep/goat	M	?	Pit with 2 sheep/goat
363	Enamel	Dog	M	?	Partial skeleton? infilling
342	Eggshell	Domestic chicken	-	Early medieval	Food offering
451	Eggshell	Domestic chicken	-	Early medieval	Food offering
479	Eggshell	Anseriform (duck/goose)	-	Early medieval	Food offering
485	Eggshell	Domestic chicken	-	Early medieval	Food offering
509	Eggshell	Nd (exotic?)	-	Early medieval	Food offering
454	Dentine	Human	M1	Early medieval	Burial
392	Dentine	Human	M2	Early medieval	Burial
22	Dentine	Human	M2	Early medieval	Burial
464	Dentine	Human	M2	Early medieval	Burial
135	Soil	-	-	-	Taken during excavation
181	Soil	-	-	-	Taken during excavation

### 3.4 Dirmstein

#### 3.4.1 Location and natural conditions

Dirmstein (district Bad Dürkheim, Rhineland-Palatinate) is approximately 10 km southeast of Bockenheim at an elevation of 108 m NHN in the Upper Rhine Valley in the north of the Palatinate region. The Haardt Mountains lie ca. 9 km to the west and the Rhine River about 14 km east from Dirmstein. After the natural division of the Rhineland-Palatinate, the region is part of the *Vorderpfälzer Riedeln* and is situated on the *Freinsheimer Riedel*, taking up the space between *Unterhaardt* und the Frankenthaler Terrace. In the south, the region borders the *Isenach-Schwemmkegel* and in the north it merges in the area of the Eckbach to the upper hill land of the Pfrimm where Bockenheim is situated<sup>14</sup>. The region is characterised by a weak undulating morphology with slight slopes ranging from west to east and heights of 100 to 150 m NHN. The geomorphological structure is determined by streams which flow from west to east. In Dirmstein, these streams are the Eckbach in the south and Floßbach in the north. Eckbach is a 39 km long stream which originated in Carlsberg in the northern Palatinate Forest and enters the Rhine River near Worms. The Floßbach is 8 km long, enters the Eckbach to the east of Dirmstein and originates as a confluence of several spring streams (Leithäuser 2011, 1–2 with references). The geological underground is mainly comprised of loess (see Fig. 10.1). This chalky, wind-blown dust silt was deposited during glacial periods in different thicknesses

<sup>14</sup> <http://www.luwg.rlp.de/Aufgaben/Naturschutz/Grundlagendaten/Naturraeumliche-Gliederung/Naturraeumliche-Gliederung-von-Rheinland-Pfalz/> (13.12.2013).

especially at the downwind side of the slopes. As a result of relocations, the loess layer can reach a thickness of 10 m. At the eastern edge of Dirmstein, erosion led to the formation of steep faces with a height of contemporary 6 m. To the south of Dirmstein, the uppermost layers are depositions of fluvial sediments<sup>15</sup>. The main part of soils is comprised of chalky chernozem made of loess. In the south, vegen and gley-vegen evolved out of carbonatic meadow silt and meadow clay. Gley-colluvisols and relictic gleys from relocated loess are found along the Floßbach<sup>16</sup>. The average temperature measures 9–10 °C and does not differ from the area of Bockenheim or the Frankenthaler Terrace. The average annual rainfall is at maximum 500 mm and therefore the region is a bit dryer than adjacent areas<sup>17</sup>.

### 3.4.2 Research history

In Dirmstein, two early medieval cemeteries were found which is indicative of a development resulting from two separate settlements. The first cemetery, which was situated in the centre of the modern village, was excavated in 1883/84 and a total of 200 graves were found. The occupation started in the early 6<sup>th</sup> century and ended in late Merovingian times (Polenz 1988, 93–99; Grünewald/Koch 2009, 494–503). The second burial site was located at the eastern village exit of Dirmstein at the edge of the former *Unterdorf* in the north of the Heuchelheimer Straße at a height of 101 m NHN in the direct vicinity of the Floßbach (Polenz 1988, 99; Leithäuser 2011, 11). First hints for the existence of this cemetery are from the year 1912. Several graves, which were found during building projects before the excavation in the years between 1986 and 1990, were either destroyed or poorly documented (Polenz 1988, 99–100; Leithäuser 2011, 11–12). A total of 284 graves were excavated by the former Department of Archaeology in Speyer. Due to several multiple and secondary burials, the total number of excavated individuals is at minimum 350 (Leithäuser 2011, 13). Even if the site was not completely excavated, the central area was mainly recorded. The archaeological evaluation was carried out by U. Leithäuser within the scope of a dissertation thesis (Leithäuser 2011). The oldest graves date to the second quarter of the 6<sup>th</sup> century (SD-phase 5) but the establishment of this site in the early 6<sup>th</sup> or late 5<sup>th</sup>

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<sup>15</sup> <http://www.luwg.rlp.de/Aufgaben/Naturschutz/Grundlagendaten/Naturraeumliche-Gliederung/Naturraeumliche-Gliederung-von-Rheinland-Pfalz/> (13.12.1013).

<sup>16</sup> [http://mapserver.lgb-rlp.de/php\\_bfd200/index.phtml](http://mapserver.lgb-rlp.de/php_bfd200/index.phtml) (23.12.2013).

<sup>17</sup> <http://www.kwis-rlp.de/index.php?id=6867> (23.12.2013).

century is possible. The occupation ended in the 8<sup>th</sup> century, during a time when the deceased were buried on church graveyards (Leithäuser 2011, 222–223). Until now, no settlement remains have been detected. The first document in which the village's name („*In villa Theormstein*“) was mentioned is from King Charles the Bald and is dated to the 23<sup>th</sup> of November, 842 (Armgarth 2005, 40–41). Dated to the year 1044, the village was traditionally denoted as *Diermundestein*, followed by *Dieremstein* from the year 1120 and *Diermestein* from 1141. The name belongs to an older accumulation of location denotations which are based of two parts, the name of a person and the suffix *-stein* (Armgarth 2005, 42–43). Remains of a Roman “stone” building have not been detected to date. Indications of Roman presence are the mentioning of a Roman stone sarcophagus and a cremation burial of the 2<sup>nd</sup> century as well as remains of a Roman gravestone in an early medieval tiled grave. Because of the good settlement conditions, the existence of Roman *villae rusticae* near Dirmstein is expected (Bernhard 2005, 5–6; Leithäuser 2011, 4).

### 3.4.3 Occupation history and interpretation

The archaeological investigation implies the coexistence of two burial communities in the earliest verifiable occupation period of the cemetery (Leithäuser 2011, 222–225). The supposed groups buried their deceased in separate areas and in different burial traditions. Despite the strong plundering and destruction of the graves, it is recognisable based on grave construction and equipment that the graves in the north-western part of the cemetery followed the Frankish burial tradition. The graves show a west-east orientation and contain wheel-made pottery in Frankish style. The oldest graves date predominantly in SD-phase 5 except grave 216 which could date to the SD-phase 4. The establishment of this western area is supposed to be before the archaeological known evidence as the northern part has not yet been excavated. Several graves cannot be assigned to either SD-phase 5 or 6 as a result of strong plundering. In the following occupation time (SD-phase 6), the western part extends further to the west and to the south (Leithäuser 2011, 222–223). The foreign origin of the second burial community in the northeastern part of the cemetery is based on the south-north orientation of the graves. These graves build a small burial group of adults and children, which may represent a family (graves 47, 28, 19, 44, and 21). The oldest grave of this group dates to SD-phase 5 and it is supposed that this part was

newly established by the immigrated group (Leithäuser 2011, 223). The south-north orientation of the graves was relatively frequent in the 5<sup>th</sup> century but almost absent in the Frankish territory in the 6<sup>th</sup> century. They are numerous in North Sea region (the “North Sea Germanic” or Anglo Saxon cultural context) with regional focus areas (Leithäuser 2011, 15–17). Other graves belonging to the eastern “foreign” group are in the east and south of the small founder burial group. Some graves contain hand-made pottery (graves 221B, 239, 254B, 19, 15, 237), whereas style, form, and decoration of some pots show “North Sea Germanic” or rather Anglo-Saxon cultural traditions (Leithäuser 2011, 160–179). This type of pottery is also known from other sites in the Upper Rhine Valley (Wieczorek 1989; Gross 1999). Furthermore, it is speculated if these finds may reflect the events which were mentioned by Procopius. He described the resettlement of men, women and children of the Anglo, Frisian and British regions to depopulated areas of the Frankish kingdom. This is, after Leithäuser, in accordance with the dating and the Anglo-Saxon focus of the pottery and the south-north orientation of the graves (Leithäuser 2011, 224). In general, these finds are considered to be evidence for the immigration of groups of non-Frankish origin as the result of planned settlement processes of the Frankish rulers in order to consolidate power in the expansion areas east and west of the Rhine (Leithäuser 2011, 224–225). An additional hint for the foreign origin of the eastern group is seen in the horse sacrifice of grave 233, as this tradition is assumed to be unknown in Frankish areas (Leithäuser 2011, 39–40). The graves 254B and 25B were circumvented by a circular ditch which is most probably the relict of a burial mound. Grave 254B, which dates to the SD-phase 6, was the burial of a young woman with numerous and precious grave goods, including hand-made pottery with “North Sea Germanic” influences. The affiliation of grave 25B to the eastern groups is only assumed because of its close vicinity to the other “foreign” graves (Leithäuser 2011, 224–225). The precious grave goods and the elaborate constructions of these graves in the eastern part of the burial site indicate remains of a foreign group of high social position and with a leadership claim in the settlement community (Leithäuser 2011, 225). The southern border of this group is marked by the graves 221B, 238, 237 and 239. A fast acculturation of the newcomers to the Frankish burial tradition shows the west-east orientation of the graves (221B) as well as an adoption of the Frankish brooch costume (254B). Only the hand-made pottery is a sign of foreign origin at that time (Leithäuser 2011, 225).

### 3.4.4 Research questions

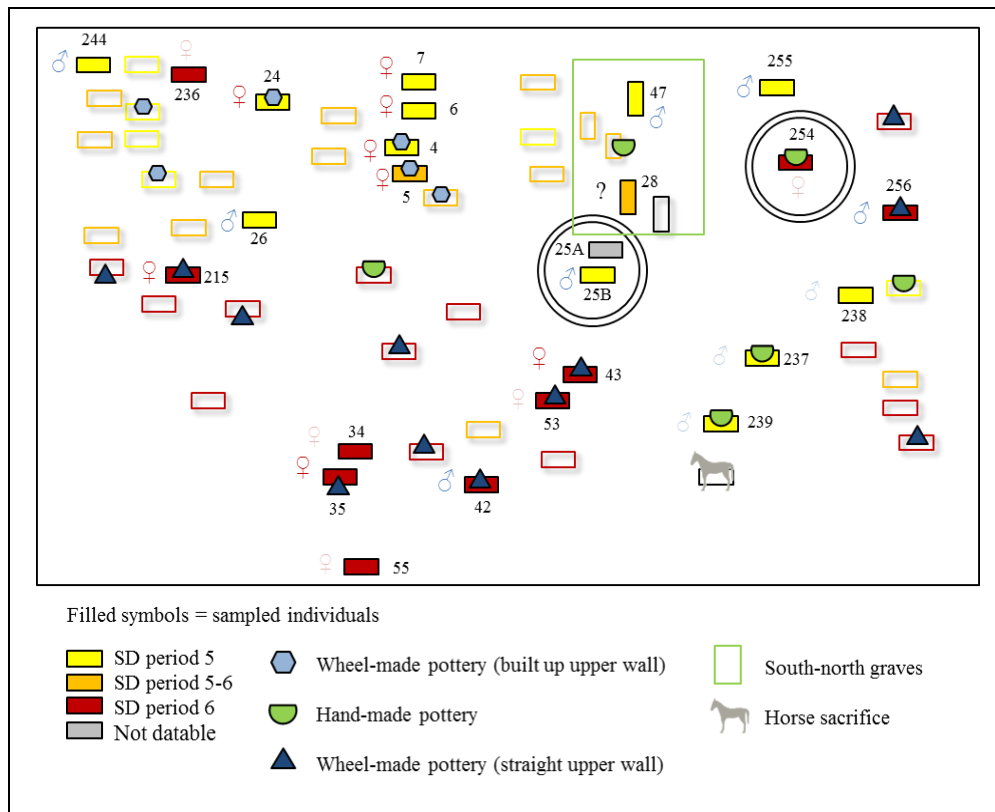
The aim of the multi-isotopic study of human tooth enamel from individuals of the cemetery of Dirmstein is the detection of local and non-local individuals. Furthermore, it will be investigated if the coexistence of two burial communities, which is postulated according to the archaeological evidence, can also be tracked by the analysis of isotopes. Additionally, the following sub-questions will be examined:

- How heterogeneous was the community during the 6<sup>th</sup> century?
- Are the “foreigners” spatially separated as indicated by the archaeological evidence?
- Do the richest graves of the cemetery represent local elites or rather elite newcomers?
- Is immigration from the North Sea area likely or are other origin areas more likely?
- Are there still newcomers in SD-phase 6?
- Are there correlations between age, sex, and social group with mobility?
- Do the grave goods reflect the cultural identity of the deceased or are other reasons for the choice of grave goods more probable? Do the goods rather represent trade networks or the origin of the families and relatives?
- Are the detected patterns comparable to those of contemporaneous graves from Bockenheim and Eppstein?
- How can the results be connected to the overall political events of the 6<sup>th</sup> century?

### 3.4.5 Samples and sampling strategy

#### 3.4.5.1 Human samples

In Dirmstein, this research project collected as many samples from the 6th century as possible. Due to poor preservation and general lack of teeth in the assemblage, it was only possible to collect 24 out of 56 datable individuals (plus one not datable individual) (Fig. 3.6, Tab. 3.5).



**Fig. 3.6. Overview of sampled individuals from Dirmstein.**

In contrast to Bockenheim and Eppstein, two teeth per individual were collected at Dirmstein, if possible, in order to investigate if the individuals changed residence during childhood and youth. If available, P2 or M2 and an additional M3 were sampled. The P2 and M2 reflect early childhood (2–8 years of age) while the M3 teeth represent late childhood and early youth (8–15 years of age). When these teeth were not available, other teeth were sampled. From two individuals three teeth were sampled. From six non-adult individuals the M1 and in one case the m1 were sampled which formed between birth (or earlier for m1) and the second year of life. In these cases, the breastfeeding effect has to be taken into account for oxygen and carbon isotope analyses. A total of 42 teeth from 25 individuals were sampled. The sex and age estimations of the sampled individuals were extracted from the catalogue of Leithäuser's publication. As a result of some discrepancies, some of the data relating to age and sex were re-evaluated.

**Tab. 3.5. Human samples from Dirmstein.**

(F/F? = female/probable female; M/M? = male/probable male; ND = not determined; ?; italicised = own observations concerning age; arc = sex based on grave goods, ant = sex based on osteological investigation; \* = definition of age groups - child: infans I, infans II; young adult: juvenile, adult I; adult: adult II, mature I; old adult: mature II, senile)

Grave	Tooth	SD-phase	Quality group	Sex arc/ant	Sex	Age	Age group*
4	P2?	5	-	F?/F	F	Adult I	Young adult
7	M	5	B1	F/F	F	Adult	Adult
24	P2, M2, M3	5	At least B	ND/(F)	F?	Adult	Adult
26	M2, M3	5	B	M/M	M	Adult	Adult
47	M2, M3	5	A2	M/M	M	Adult	Adult
237	M1	5	-	M/ND	M	Infans I	Child
238	M1	5	-	M/ND	M	Infans I	Child
239	P2, M2, M3	5	B2	M/ND	M	Juvenile-adult I	<i>Adult</i>
244	M2, M3	5	B2	M/M	M	Mature II	Old adult
255	M1, M3	5	B	M/M	M	Mature II	Old adult
6	M2, M3	5?	-	ND/F	F	Adult	Adult
25b	P2, M3	5?	C	M/(M)	M	Adult	Adult
5	M2, M3	5-6	B	F/F	F	Adult I	Young adult
28	C, P	5-6	-	ND/ND	ND	ND	Adult
34	M1	6	A	F/F	F	Infans II	Child
42	M1?	6	A?	M/M	M	Mature II	Old adult
43	M2, M3	6	B1	F/F	F	Adult I	Young adult
53	M1	6	A?	F/ND	F	Infans I	Child
55	M1	6	-	F/ND	F	Infans I	Child
215	M2	6	-	F/F	F	Adult II	Adult
236	m1	6	B	F/ND	F	Infans I	Child
254	M2, M3	6	C	F/(F)	F	Juvenile	Young adult
256	M2, M3	6	At least A2	M/M	M	Adult	Adult
35	M2, M3	6	B	F/ND	F	Adult	Adult
25a	P2, M3	ND	-	ND/M	M	Mature II	Old adult

#### 3.4.5.2 Samples for the local strontium range

For the determination of the biologically available strontium signature at the site of Dirmstein, faunal tooth enamel and dentine samples, eggshells, as well as human dentine samples and two soil samples were collected (Tab. 3.6). The faunal teeth include samples from seven animals including two cattle, two pigs, one sheep/goat, one canid, and one horse. Most of the faunal samples were recovered from the grave infillings, whereby their exact temporal relationship to the humans interred in the graves is unclear. Exceptions are the eggshells from domestic chicken of the graves 24 and 35, which were placed as food offerings, and the horse tooth which probably belongs to the early medieval horse sacrifice of grave 233. In addition to the bulk samples, the horse and two cattle teeth were sampled at three points along the axis of

the teeth in order to achieve a time sequence and to capture lifetime movement histories. Taxonomic identification of the eggshells was performed with a highly sensitive mass spectrometry and the peptide mass fingerprinting (ZoomS) method by John Stewart (Stewart et al. 2013). The identification of faunal bone and teeth material was conducted by Anja Prust. Soil samples from graves 170 and 226 were attached to the skeletal remains of these graves.

**Tab. 3.6. Samples for the determination of the local strontium range at Dirmstein.**

Grave	Material	Species	Tooth	Date	Context
148a	Enamel, dentine	Cattle	M	?	Single tooth, box find
263	Enamel, dentine	Cattle	M2	ND	Complete skull, stray find
106	Enamel, dentine	Pig	I	ND	Several teeth, stray find
230	Enamel, dentine	Pig	P3	ND	Single tooth, box find
112	Enamel, dentine	Sheep/goat	M1?	ND	Single tooth, stray find
39	Enamel, dentine	Canis	C	Modern?	Single tooth, stray find
234	Enamel, dentine	Horse	M	Early medieval	Single tooth, stray find
24	Eggshell	Domestic chicken	-	Early medieval	Food offering
35	Eggshell	Domestic chicken	-	Early medieval	Food offering
215	Dentine	Human	M2	Early medieval	Burial
5	Dentine	Human	M2	Early medieval	Burial
42	Dentine	Human	M1?	Early medieval	Burial
43	Dentine	Human	M2	Early medieval	Burial
170	Soil	-	-	-	Attached to bone
226	Soil	-	-	-	Attached to bone

#### 3.4.5.3 Cattle samples for oxygen and carbon isotope analysis

Furthermore, the M2 and M3 of the cattle skull from grave 263 were sequentially sampled for oxygen and carbon isotope analysis. The skull was found in the grave infilling and the temporal context is unclear. The sequential sampling for oxygen and carbon isotope analyses was mainly performed in order to test the preparation technique. Furthermore, it is expected that the samples show a sinusoidal pattern reflecting seasonal variation within a year with increased values in summer and decreased values in winter. If the pattern is observed, this shows that the samples and therefore also indirectly most probably also the human teeth are not (strongly) diagenetically altered. In addition, the results will give a general overview about the seasonal variation of  $\delta^{18}\text{O}$  (and  $\delta^{13}\text{C}$ ) values in the northern Upper Rhine Valley, provided the animals obtained food locally from the Upper Rhine Valley which will be detected by analysing the  $^{87}\text{Sr}/^{86}\text{Sr}$  values.



## 4 Methods

### 4.1 Strontium isotope analysis

#### 4.1.1 Sample preparation I

Cleaning and sampling of the samples for the strontium isotope analysis was conducted at the Leibniz-Laboratory for Radiometric Dating and Isotope Research, Kiel. Human tooth samples were first cleaned in high-purity demineralised water and then dried overnight at 60 °C. The surface of each tooth crown was removed using a tungsten carbide dental burr. A longitudinal thin section of enamel representing the complete growth axis was separated from every tooth with a diamond-edged dental saw disc. All surfaces of the pieces were abraded with a dental drill in order to remove dentine and micro-cracks or other discoloured areas. Dentine samples were taken with the same procedure from the primary crown dentine and the attached enamel was removed. Enamel and dentine samples were cleaned again in an ultrasonic bath to remove dust, dried at room temperature and then stored in clean containers until further preparation. Faunal archaeological tooth samples were first cleaned in high-purity demineralised water and then dried overnight at 60 °C. The surface of each tooth crown was thoroughly cleaned using a tungsten carbide dental burr. From each tooth a longitudinal section of enamel representing the complete growth axis was separated with a diamond-edged dental saw disc. Some samples were additionally sampled sequentially. In these cases, small slices of enamel were sampled at the tip, in the middle and the margin of the tooth (cattle and horse). Teeth with smaller crowns were only sampled at the tip and the margin of the tooth (pig). All surfaces of the pieces were abraded with a dental drill in order to remove dentine and micro-cracks or other discoloured areas. Samples were cleaned again in an ultrasonic bath to remove dust, dried at room temperature and then stored in clean containers until further preparation. Dentine samples were taken from the area directly adjacent to the site of the enamel removal and prepared the same way as the enamel samples. Tooth enamel samples from the modern deer samples were also generally prepared in the same way but the teeth were still in the jaw. Eggshell samples were first cleaned in high-purity demineralised water and then dried overnight at 60 °C. The surfaces of the small eggshells pieces were carefully abraded using a scalpel. Samples were then cleaned in high-purity demineralised water, dried at room temperature and stored in

clean containers until further preparation. Soil samples weighing around 50 mg were transferred to clean containers without further preparation. Water samples were directly stored in a refrigerator after sampling in the field.

### **4.1.2 Sample preparation II**

Further processing of the samples was done at the GEOMAR-Helmholtz Centre for Ocean Research, Kiel. First, all tooth (enamel and dentine) and eggshell samples were weighed in Teflon beakers. Then, samples were dissolved in 1 ml 8 N HNO<sub>3</sub> and a few drops H<sub>2</sub>O<sub>2</sub> on a hotplate at 100 °C for at least 3 hours in closed beakers. After digestion, beakers were opened and the sample solutions were evaporated to dryness at ~60 °C. The residue was redissolved in 5 ml 2% concentrated HNO<sub>3</sub>. Soil samples were digested in 3 ml concentrated HNO<sub>3</sub> and 2 ml HF and left on the hotplate for several days at 120 °C. Then, the acids were evaporated and the residue was dissolved again in 3 ml concentrated HNO<sub>3</sub> and 2 ml HF for several days. After evaporation, the residue was taken up in 1 ml 8 N HNO<sub>3</sub> and a few drops of H<sub>2</sub>O<sub>2</sub> and put on a hotplate. After digestion, vials were opened and the sample solutions were evaporated to dryness. The residue of each sample was redissolved in 5 ml 2% concentrated HNO<sub>3</sub>.

### **4.1.3 Extraction**

For the strontium extraction, an aliquot of each sample containing about 500 ng (in some cases 1500 ng) of strontium was evaporated and the residue was dissolved in 1 ml 8 N HNO<sub>3</sub>. The strontium was separated from the sample matrix by ion exchange chromatography. First, columns were checked for functionality by filling with Ethanol and then with 2 ml water to remove the Ethanol. Then, about 50–100 µl of Eichrom SrSpec resin were pipetted into the columns. In order to purify the resin from contaminants, the columns were washed two times alternately with 3 ml 8 N HNO<sub>3</sub> and 3 ml ultrapure water. The resin was conditioned with 3 ml 8 N HNO<sub>3</sub> and the sample solutions were added to columns. The columns were sequentially washed with 4 ml 8 N HNO<sub>3</sub> in order to catch the strontium and to wash out disturbing Rb. Strontium was released into pre-cleaned Teflon beakers by washing the columns with

6 ml 0,05 N HNO<sub>3</sub>. The collected sample solutions were evaporated, cleaned with a mixture of concentrated HNO<sub>3</sub> and H<sub>2</sub>O<sub>2</sub> and evaporated to dryness.

#### **4.1.4 Measurement**

Strontium concentrations were measured by ICP-MS-Quadrupole Agilent 7500cx. The measurements were conducted by A. Koelvica. The <sup>87</sup>Sr/<sup>86</sup>Sr measurements were carried out using MC-ICP-MS “AXIOM”. Solutions were prepared using 5% HNO<sub>3</sub>. The isotope measurements were conducted by J. Fietzke. The standard error for the Sr isotope ratio measurements is less than 0.00001. The <sup>87</sup>Sr/<sup>86</sup>Sr measurements of the internal standard reference material NBS987 yielded an average value of 0.710257 ± 0.000026 (2σ, n = 23).

## **4.2 Oxygen and carbon isotope analysis**

All oxygen and carbon isotope measurements were prepared on the structural carbonate component of bioapatite of tooth enamel. The pretreatment and measurement of the samples was conducted at the Leibniz-Laboratory for Radiometric Dating and Isotope Research, Kiel, Germany.

### **4.2.1 Pretreatment**

#### *4.2.1.1 Pretreatment experiments*

In order to test the effect of different pretreatment methods and the effect of heat on δ<sup>18</sup>O and δ<sup>13</sup>C, several experiments were performed. The first experiments were conducted on a modern human tooth from a dental practice and an ancient human tooth of unknown age. First, both teeth were separated in two parts with a diamond-edged dental saw disc. Then, the parts were cleaned ultrasonically in high-purity demineralised water. One part of each tooth (modern and ancient) was dried overnight at 60 °C, the other parts were air-dried. Tooth enamel of each subsample was completely separated from the dentine using a tungsten carbide dental burr. All surfaces of the pieces were abraded with a dental drill in order to remove dentine, cracks, carious or discoloured areas. After the samples were again cleaned in an ultrasonic bath and dried at room temperature, the pieces were ground to a fine

powder using agate pestle and mortar. The powdered enamel of each subsample was again separated into three aliquots weighing between ca. 0.8 to 5 mg, transferred to 0.2 ml Eppendorf tubes and treated according to the protocols as summarised in Tab. 4.1. Aliquots of the protocols 3–6 were rinsed and centrifuged five times with distilled water after each step and then freeze-dried overnight.

**Tab. 4.1. Treatment protocols experiment I.**

Protocol	Drying	1 <sup>st</sup> step	2 <sup>nd</sup> step
1	60 °C	Untreated	Untreated
2	Air-dried	Untreated	Untreated
3	60 °C	3% NaOCl 24h	0.1 M acetic acid 3h
4	Air-dried	3% NaOCl 24h	0.1 M acetic acid 3h
5	60 °C	3% NaOCl 30min	0.1 M acetic acid 10min
6	Air-dried	3% NaOCl 30min	0.1 M acetic acid 10min

The second round of experiments was conducted on teeth of the three early medieval sites from the Upper Rhine Valley. From each site, five teeth were selected randomly. First, each tooth was cleaned ultrasonically in high-purity demineralised water and then dried overnight at 60 °C. For one site (Dirmstein), the teeth were separated in two parts with a diamond-edged dental saw disc before the ultrasonic bath. One part was dried overnight at 60 °C and the other part was air-dried. Tooth enamel of each subsample was completely separated from the dentine using a tungsten carbide dental burr. All surfaces of the pieces were abraded with a dental drill in order to remove dentine, cracks, carious or discoloured areas. After the samples were cleaned again in an ultrasonic bath and dried at room temperature, the pieces were ground to a fine powder using agate pestle and mortar. The powdered enamel of each subsample was again separated in several aliquots weighing between 0.8 to 5 mg, transferred to 0.2 ml Eppendorf tubes and treated according to the protocols A to DD as summarised in Tab. 4.2. Aliquots were rinsed and centrifuged five times with distilled water after each step and then freeze-dried overnight.

**Tab. 4.2. Treatment protocols experiment II.**

Protocol	Drying	1 <sup>st</sup> step	2 <sup>nd</sup> step	Comment
A	Air-dried	-	-	Only Dirmstein
AA	60 °C	-	-	All samples
B	60 °C	3% NaOCl 30min	-	All samples
BB	60 °C	3 % NaOCl 24h	-	All samples
C	60 °C	0.1 M acetic acid 10min	-	All samples
CC	60 °C	0.1 M acetic acid 2h	-	All samples
D	60 °C	3% NaOCl 30min	0.1 M acetic acid 10min	All samples
DD	60 °C	3 % NaOCl 24h	0.1 M acetic acid 2h	All samples

#### *4.2.1.2 Human tooth enamel*

Oxygen and carbon isotope measurements were prepared on the structural carbonate component of bioapatite of 137 human tooth enamel samples. First, each tooth was cleaned ultrasonically in high-purity demineralised water and then dried overnight at 60 °C. The surface of each tooth crown was removed using a tungsten carbide dental burr. A small piece of enamel (bulk) spanning the entire vertical axis of tooth growth was separated from every tooth with a diamond-edged dental saw disc. All surfaces of the pieces were abraded with a dental drill in order to remove dentine, cracks, carious or discoloured areas. After the samples were again cleaned in an ultrasonic bath and dried at room temperature, the pieces were ground to a fine powder using agate pestle and mortar. Enamel powder of each sample was transferred in 0.2 ml Eppendorf tubes and treated with 0.1 M acetic acid for 10 minutes (0.1 ml/mg) to remove exogenous and adsorbed carbonate. Aliquots weighing between 0.8 to 5 mg were rinsed and centrifuged five times with distilled water and then freeze dried overnight.

#### *4.2.1.3 Cattle tooth enamel*

Four pairs of second and third cattle molars with high crowns were sequentially sampled for  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ . The teeth were found in pits of the cemeteries Bockenheim and Dirmstein and could not be attributed to a specific SD-phase. First, each tooth was cleaned ultrasonically in high-purity demineralised water and then dried overnight at 60 °C. Then, cementum was removed and tooth surfaces were cleaned using a tungsten carbide dental burr. A sequence of horizontal bands of enamel was sampled from the top to the bottom of the crown through the whole enamel layer using a diamond drill. Between eight and 14 intra-tooth samples of powdered enamel were obtained. In some cases, pieces were cut off, cleaned and powdered with pestle and mortar. Enamel powder of each sample was transferred in 0.2 ml Eppendorf tubes and treated with 0.1 M acetic acid for 10 minutes (0.1 ml/mg) to remove exogenous and adsorbed carbonate. Aliquots weighing between 0.8 to 5 mg were rinsed and centrifuged five times with distilled water and then freeze-dried overnight.

### 4.2.2 Measurement

The stable isotopic composition of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  of the tooth enamel samples was measured with a Finnigan MAT 253 interfaced with a Kiel IV device. Powdered samples were reacted with 100% phosphoric acid at 70 °C in individual vessels in an automated cryogenic distillation system (Kiel IV device), interfaced with a Finnigan MAT 253 isotope ratio mass spectrometer. The external precision is better than  $\pm 0.05$  for  $\delta^{13}\text{C}$  and better than  $\pm 0.07\text{‰}$  for  $\delta^{18}\text{O}$ . Results were calibrated using the National Institute of Standards and Technology NBS19 as well as several internal standards. The data are given in  $\delta$ -notation, standardised to the Vienna Pee Dee Belemnite (VPDB).

### 4.3 Statistical analysis

Statistical analyses were performed using the software SPSS version 21 and Excel 2010. The statistical Shapiro-Wilk test in combination with graphical tools, such as a histogram with a normal curve and a normal Q-Q plot, was used to test whether each dataset was normally distributed. When a sample's size for a data set was less than 20, it was assumed to have a non-normal distribution as the probability of failing the null hypotheses increases. Because most of the tested data sets were not normally distributed, all data were assumed to be non-normally distributed, for comparative statistical purposes. As oxygen and carbon isotopes are ordinal (type of percentage) and do not show quantity but rank, the use of parametric statistics is precluded. Therefore, only non-parametric statistics were used. The test of choice in order to compare differences between two independent groups was the two-tailed Mann-Whitney U test. This test does not assume equality of variance or normal distribution between two sets of samples. Furthermore, it does not require sample sets to possess an equal number of observations and is essentially equivalent to a parametric independent-sample t-test. The null hypothesis states that there is no difference between the ranks of two samples. A probability level of 5% was considered significant to reject the null hypothesis.

### III. RESULTS

## 5 Strontium isotope analysis

### 5.1 Human data

#### 5.1.1 Complete sample set

The strontium concentrations and isotope compositions were determined for 137 human enamel samples from 120 individuals. The results are listed in Tab. 5.1. Only one tooth was analysed from 105 individuals, two teeth from 13 individuals and three teeth from two individuals. The  $^{87}\text{Sr}/^{86}\text{Sr}$  of the complete sample set lies between 0.70819 and 0.72938 with a mean of  $0.71010 \pm 0.00261$  ( $1\sigma$ ). There are some extreme radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values above 0.71032 up to 0.72938 which differ obviously from the main bulk of samples. The strontium concentrations range from 36 to 326 ppm with a mean of  $128 \pm 51$  ppm ( $1\sigma$ ). The strontium concentrations are within the typical range for reported modern human teeth, ranging between approximately 40 and 400 ppm (Montgomery 2002, 71; Schweissing/Grupe 2003b, 1375). However, it is apparent that most of the samples cluster between 50 and 175 ppm and few are higher than 200 ppm. Neither the strontium concentration nor the isotope composition is normally distributed (see Fig. 10.2).

**Tab. 5.1. Results  $^{87}\text{Sr}/^{86}\text{Sr}$  and Sr ppm of the complete human enamel data set.**

Site	Grave	Tooth	SD-phase	Sex	Age group	$^{87}\text{Sr}/^{86}\text{Sr}$	2SD	SE	ppm
Boc	22	M2	5-6	M	Adult	0.70934	0.00002	0.00001	114
Boc	382	M2	6-7	F	Old adult	0.70994	0.00002	0.00001	59
Boc	386	P1	6-7	ND	Adult	0.70936	0.00002	0.00001	151
Boc	391	M2	2-3	F?	Adult	0.70936	0.00002	0.00001	88
Boc	392	M2	4-7	F	Old adult	0.70976	0.00002	0.00001	44
Boc	395	M1	5-6	F	Child	0.70938	0.00002	0.00001	98
Boc	396	M2	4-7	F	Child	0.70820	0.00002	0.00001	77
Boc	397	P2	4-7	F	Young adult	0.70911	0.00002	0.00001	79
Boc	398	P2	7-8	M	Old adult	0.70819	0.00002	0.00001	92
Boc	406	M2	4-5	F	Old adult	0.70970	0.00002	0.00001	72
Boc	421	P2	6-7	M	Young adult	0.70927	0.00002	0.00001	130
Boc	423	M1	5-6	ND	Child	0.70928	0.00002	0.00001	61
Boc	424	M2	5	F	Adult	0.70977	0.00002	0.00001	82
Boc	449	M1	3-4	F	Child	0.70965	0.00002	0.00001	127
Boc	454	P2	5	M?	Adult	0.70964	0.00002	0.00001	231
Boc	457	M2?	4-5	M?	Young adult	0.70947	0.00002	0.00001	94
Boc	459	M2	6	M	Adult	0.70916	0.00002	0.00001	71

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Boc	461	M1	4-7	ND	Child	0.70987	0.00002	0.00001	114
Boc	464	M2	5	?	Young adult	0.70906	0.00002	0.00001	197
Boc	466	P2?	6	M	Adult	0.70835	0.00002	0.00001	74
Boc	470	M2	6	F	Young adult	0.70923	0.00002	0.00001	152
Boc	473	M1	5-7	F	Child	0.70928	0.00002	0.00001	118
Boc	474	M2	4-7	F	Adult	0.70935	0.00002	0.00001	157
Boc	478	M2	6-7	F?	Adult	0.70848	0.00002	0.00001	201
Boc	480	M1	4-7	M?	Child	0.70958	0.00002	0.00001	93
Boc	482	M2	3	F	Adult	0.71032	0.00002	0.00001	119
Boc	486	M2	3-4	F	Adult	0.70886	0.00002	0.00001	78
Boc	488	M2	3	F	Young adult	0.70902	0.00002	0.00001	64
Boc	492	P2	6-7	F?	Old adult	0.70987	0.00002	0.00000	143
Boc	497	P2	4-7	F?	Adult	0.70974	0.00002	0.00001	126
Dir	4	P2?	5	F	Young adult	0.70983	0.00002	0.00001	80
Dir	5	M2	5-6	F	Young adult	0.70982	0.00002	0.00001	93
Dir	5	M3	5-6	F	Young adult	0.70970	0.00002	0.00001	109
Dir	6	M2	5?	F	Adult	0.71271	0.00002	0.00001	84
Dir	6	M3	5?	F	Adult	0.71073	0.00002	0.00001	206
Dir	7	M	5	F	Adult	0.70982	0.00002	0.00001	61
Dir	24	P2	5	F?	Adult	0.70949	0.00002	0.00001	98
Dir	24	M2	5	F?	Adult	0.70944	0.00002	0.00001	286
Dir	24	M3	5	F?	Adult	0.70950	0.00002	0.00001	104
Dir	25a	P2	ND	M	Old adult	0.70963	0.00002	0.00001	130
Dir	25a	M3	ND	M	Old adult	0.70957	0.00002	0.00001	121
Dir	25b	P2	5?	M	Adult	0.71191	0.00002	0.00001	122
Dir	25b	M3	5?	M	Adult	0.70953	0.00002	0.00001	146
Dir	26	M2	5	M	Adult	0.70920	0.00002	0.00001	111
Dir	26	M3	5	M	Adult	0.70915	0.00002	0.00001	135
Dir	28	C	5-6	ND	Adult	0.72204	0.00002	0.00001	132
Dir	28	P	5-6	ND	Adult	0.72405	0.00002	0.00001	149
Dir	34	M1	6	F	Child	0.71000	0.00002	0.00001	56
Dir	35	M2	6	F	Adult	0.71119	0.00002	0.00001	137
Dir	35	M3	6	F	Adult	0.71180	0.00002	0.00001	132
Dir	42	M1?	6	M	Old adult	0.71027	0.00002	0.00001	70
Dir	43	M2	6	F	Young adult	0.71005	0.00002	0.00001	111
Dir	43	M3	6	F	Young adult	0.70989	0.00002	0.00001	143
Dir	47	M2	5	M	Adult	0.70932	0.00002	0.00001	75
Dir	47	M3	5	M	Adult	0.70910	0.00002	0.00001	124
Dir	53	M1	6	F	Child	0.70973	0.00002	0.00001	88
Dir	55	M1	6	F	Child	0.71020	0.00002	0.00001	84
Dir	215	M2	6	F	Adult	0.70981	0.00002	0.00001	68
Dir	236	m1	6	F	Child	0.70982	0.00002	0.00001	124
Dir	237	M1	5	M	Child	0.70969	0.00002	0.00001	153
Dir	238	M1	5	M	Child	0.70980	0.00002	0.00001	90
Dir	239	P2	5	M	Adult	0.71011	0.00002	0.00001	110
Dir	239	M2	5	M	Adult	0.71001	0.00002	0.00001	103
Dir	239	M3	5	M	Adult	0.70988	0.00002	0.00001	128



Dir	244	M2	5	M	Old adult	0.72938	0.00002	0.00002	36
Dir	244	M3	5	M	Old adult	0.71653	0.00002	0.00001	99
Dir	254b	M2	6	F	Young adult	0.70968	0.00002	0.00001	157
Dir	254b	M3	6	F	Young adult	0.70955	0.00002	0.00001	193
Dir	255	M1	5	M	Old adult	0.70901	0.00002	0.00001	81
Dir	255	M3	5	M	Old adult	0.70888	0.00002	0.00001	119
Dir	256	M2	6	M	Adult	0.71076	0.00002	0.00000	97
Dir	256	M3	6	M	Adult	0.71186	0.00002	0.00001	122
Epp	3	M2	6-7	M	Adult	0.70916	0.00002	0.00001	99
Epp	4C	M2	6-7	F	Young adult	0.70900	0.00002	0.00001	171
Epp	25	M2	6?	M	Child	0.70959	0.00002	0.00001	281
Epp	29	M	6	F	Adult	0.70863	0.00002	0.00001	135
Epp	30	P	6	F	Old adult	0.70996	0.00002	0.00001	184
Epp	35	M2	4	M	Adult	0.71242	0.00002	0.00001	122
Epp	37	M2	4-5?	M	Young adult	0.70937	0.00002	0.00001	146
Epp	38	M2	5	M	Adult	0.70923	0.00002	0.00001	117
Epp	39	M2	6?	F	Old adult	0.70932	0.00002	0.00001	207
Epp	46	M2	5	M	Young adult	0.70927	0.00002	0.00001	223
Epp	47	M2	4-5?	M?	Adult	0.71010	0.00002	0.00001	91
Epp	48	M2	4	M	Young adult	0.70910	0.00002	0.00001	156
Epp	49	M2	4?	M?	Adult	0.70898	0.00002	0.00001	221
Epp	50	M3?	2-3	ND	Adult	0.70821	0.00002	0.00001	204
Epp	52	M1?	2	M?	Adult	0.71199	0.00002	0.00001	86
Epp	55	P2	6	F	Adult	0.70940	0.00002	0.00001	146
Epp	58	P2	4-5?	?	Adult	0.70905	0.00002	0.00001	88
Epp	61	M2	6	F?	Adult	0.70843	0.00002	0.00001	326
Epp	62	M2	5-6	M	Young adult	0.71115	0.00002	0.00001	127
Epp	66	M2?	2-3?	ND	Young adult	0.71336	0.00002	0.00001	99
Epp	67A	C?	5?	F	Old adult	0.70846	0.00002	0.00001	252
Epp	67C	M2?	2	F	Young adult	0.70861	0.00002	0.00001	69
Epp	70	M1?	6	F	Old adult	0.70850	0.00002	0.00001	106
Epp	71	M2	6/7?	M	Old adult	0.70898	0.00002	0.00001	178
Epp	74	M2	6-7	M	Adult	0.71029	0.00002	0.00001	126
Epp	83	M2	3	F	Young adult	0.71031	0.00002	0.00001	73
Epp	111	M2	5	M	Young adult	0.70954	0.00002	0.00001	102
Epp	162	M2	6	M	Young adult	0.70922	0.00002	0.00001	243
Epp	167	P2	6	?	Young adult	0.70879	0.00002	0.00001	145
Epp	168	M1	6	M	Child	0.70949	0.00002	0.00001	156
Epp	182	M1	6	M	Child	0.70969	0.00002	0.00001	116
Epp	188	M2	6?	F	Adult	0.70918	0.00002	0.00001	97
Epp	189	M1	5	?	Child	0.70946	0.00002	0.00001	86
Epp	192	M1	5	F?	Child	0.70951	0.00002	0.00001	148
Epp	197	M2?	6	F	Young adult	0.70904	0.00002	0.00001	166
Epp	198	M2	6	F	Young adult	0.70931	0.00002	0.00001	120
Epp	208	M2	5-6	ND	Adult	0.70916	0.00002	0.00001	101
Epp	211	P1	5(-6)	?	Adult	0.70976	0.00002	0.00001	111
Epp	217	M1?	6	F	Child	0.70963	0.00002	0.00001	187

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Epp	222	P1	5	M	Adult	0.70930	0.00002	0.00001	128
Epp	224	m1	6	M	Child	0.70932	0.00002	0.00001	163
Epp	226	M2	6	F	Adult	0.70985	0.00002	0.00001	118
Epp	228	M2	6	F	Young adult	0.70914	0.00002	0.00001	167
Epp	233	P2	6-7	M	Adult	0.70928	0.00002	0.00001	152
Epp	245	M1	6-7	ND	Child	0.70958	0.00002	0.00001	149
Epp	246	M2	6	M	Adult	0.70925	0.00002	0.00001	117
Epp	275	M3?	2	ND	Adult	0.71028	0.00002	0.00001	176
Epp	279	M	6	M	Adult	0.70936	0.00002	0.00001	113
Epp	280	P2	2?	F?	Adult	0.70907	0.00002	0.00001	54
Epp	391	P?	6	M	Adult	0.70868	0.00002	0.00001	211
Epp	396	M2	2	M	Young adult	0.71107	0.00002	0.00001	119
Epp	405	M2	6	M	Old adult	0.71258	0.00002	0.00001	235
Epp	411	M1	5	F	Child	0.70947	0.00002	0.00001	135
Epp	413	M2	5?	F	Young adult	0.70889	0.00002	0.00001	109
Epp	418	M2?	5	F?	Adult	0.70990	0.00002	0.00001	105
Epp	421	P?	6	F	Adult	0.70972	0.00002	0.00001	151
Epp	422	M1	6	M	Child	0.70954	0.00002	0.00001	196
Epp	425	M2	4?	M	Young adult	0.70874	0.00002	0.00001	130
Epp	426B	P2	5?	M	Young adult	0.70949	0.00002	0.00001	168
Epp	428	m1?	3-5?	ND	Child	0.70944	0.00002	0.00001	128
Epp	431	P1	4?	F	Adult	0.71578	0.00002	0.00001	83
Epp	433	M2	4	F	Young adult	0.70976	0.00002	0.00001	149
Epp	435	M1	6	F	Child	0.70899	0.00002	0.00001	154
Epp	436	M2	4-5	M	Old adult	0.70924	0.00002	0.00001	63
Epp	437	M2	4?	M	Young adult	0.71364	0.00002	0.00001	79

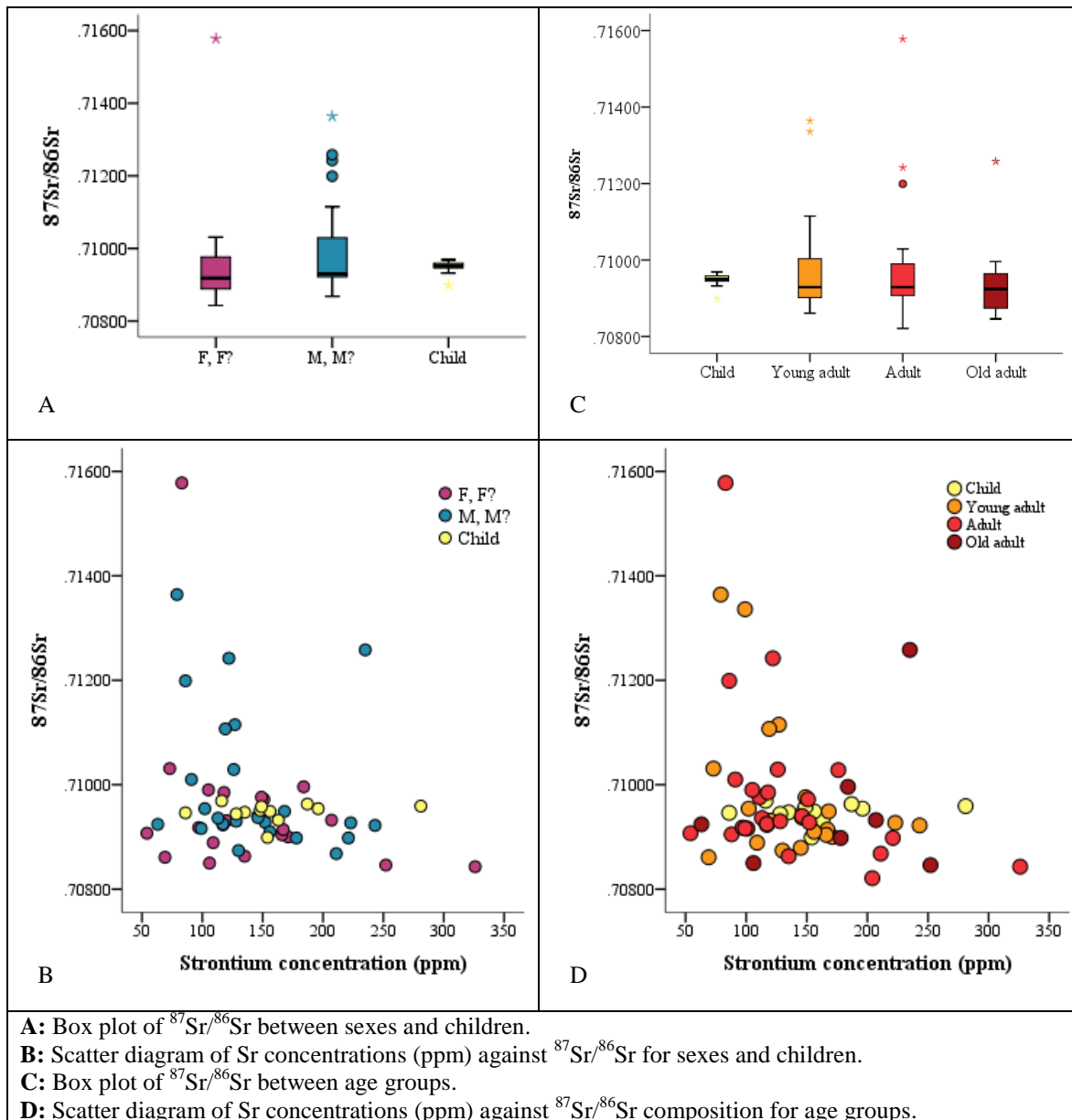
### 5.1.2 Eppstein

The strontium concentrations and isotope ratios of 65 individuals from the cemetery of Eppstein were measured. Results are presented in Fig. 5.1, Fig. 5.2 and Tab. 5.1. One tooth per individual was sampled. When M2 and P2 were not available, other teeth were sampled (see Tab. 5.2).

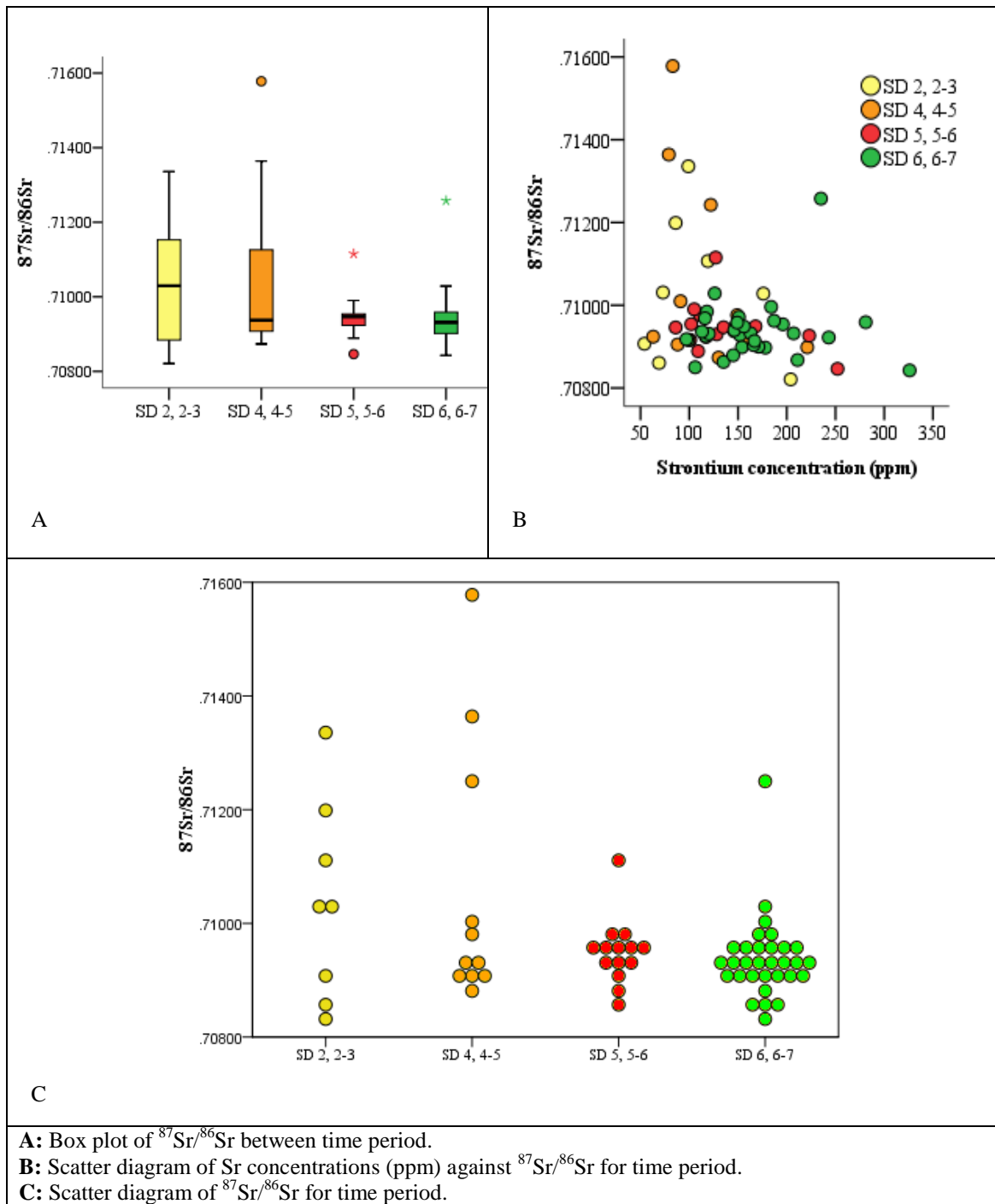
**Tab. 5.2. Eppstein samples per tooth type.**

Tooth	Number
M2 (M2?)	30 (5)
M3?	2
M	2
P2	6
P1	3
P (P?)	1 (2)
C?	1
M1 (M1?)	8 (3)
m1 (m1?)	1 (1)

The strontium isotope ratios vary between 0.70821 and 0.71578 (mean:  $0.70972 \pm 0.00132$ ,  $1\sigma$ ). The samples are not normally distributed ( $p = 0.000$ ) and have a skewness toward more radiogenic values. The strontium concentrations range between 54 and 326 ppm with a mean of  $144 \pm 54$  ppm ( $1\sigma$ ) ( $p = 0.006$ ) (see appendix Fig. 10.5). It is noticeable that some male individuals have more radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values than most of the female individuals (excluding children), but the difference is not significant (female: mean =  $0.70954 \pm 0.00153$ ,  $1\sigma$ ,  $n = 21$ ; male: mean =  $0.70998 \pm 0.00136$ ,  $1\sigma$ ,  $n = 25$ ;  $p = 0.137$ ). An exception is one female individual that has the most radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  value (0.71578) of the complete human enamel data set from Eppstein. Children show a restricted range in both the strontium isotope composition (mean =  $0.70947 \pm 0.00018$ ,  $n = 12$ ) and the strontium concentration (mean =  $158 \pm 49$  ppm). Two children are exceptional; one with an elevated strontium concentration of around 300 ppm and another with a slightly lower  $^{87}\text{Sr}/^{86}\text{Sr}$  value than most of the children (0.70899). There are no significant differences in mean  $^{87}\text{Sr}/^{86}\text{Sr}$  values between age groups (children:  $0.70947 \pm 0.00018$ ,  $1\sigma$ ,  $n = 12$ ; young adults:  $0.70984 \pm 0.00143$ ,  $1\sigma$ ,  $n = 20$ ; adult:  $0.70979 \pm 0.00154$ ,  $1\sigma$ ,  $n = 26$ ; old adult:  $0.70958 \pm 0.00142$ ,  $1\sigma$ ,  $n = 7$ ). Some more radiogenic values are present in all age classes except children. Even if there are no statistically significant differences between the time periods, the scatter plot and the box plot show that there are still differences between time periods. The strontium isotope range of the two earliest periods shows a larger variability than the later periods. There are some more radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values in the earliest SD-phases and the strontium concentrations have also more extreme values (Fig. 5.2).



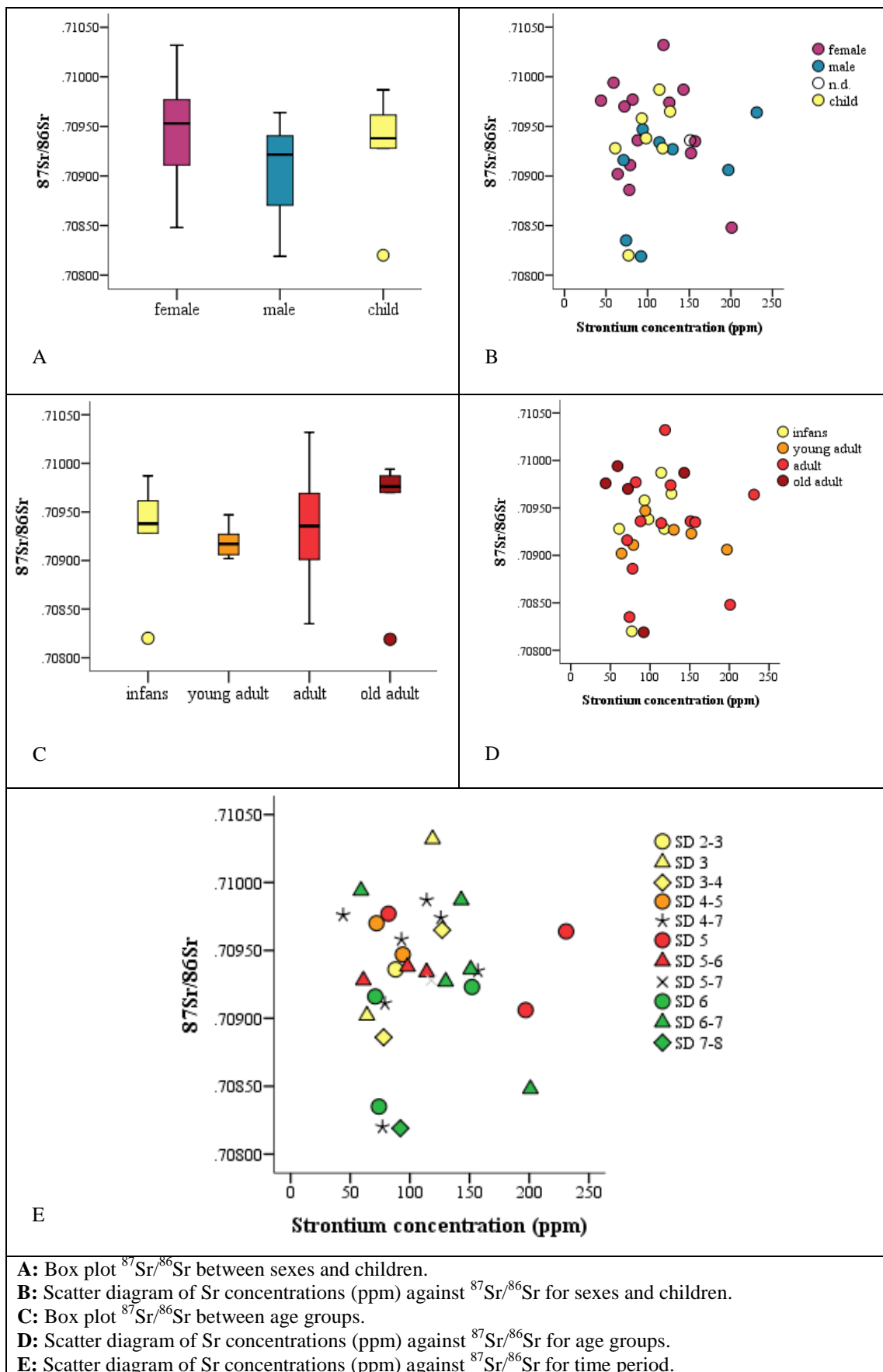
**Fig. 5.1. Eppstein Sr ppm and  $^{87}\text{Sr}/^{86}\text{Sr}$  by sex and age groups.**



**Fig. 5.2. Eppstein Sr ppm and  $^{87}\text{Sr}/^{86}\text{Sr}$  by time period.**

### 5.1.3 Bockenheim

The strontium concentrations and strontium isotope ratios of 30 individuals from the cemetery of Bockenheim were determined. The results are presented in Fig. 5.3 and Tab. 5.1. One tooth per individual was sampled. With the exception of teeth from children, whose first molars were mainly sampled, only premolars and second molars were analysed from adult individuals. The  $^{87}\text{Sr}/^{86}\text{Sr}$  values of the complete data set range from 0.70819 to 0.71032 with a mean of  $0.70932 \pm 0.00051$  ( $1\sigma$ ). Four outliers which exhibit values below 0.7085 are noticeable. The strontium concentrations range between 44 to 231 ppm with a mean of  $110 \pm 45$  ppm ( $1\sigma$ ). Most of the samples have strontium concentrations between 50 and 100 ppm, with the frequency decreasing towards 250 ppm. Neither the strontium concentration ( $p = 0.032$ ) nor the isotope composition show a clearly normal distributed pattern ( $p = 0.080$ ) (see appendix Fig. 10.3). Strontium isotopic differences between different groups according to age and sex are minimal. Adult female individuals tend to have more radiogenic strontium isotope values than adult male individuals but the difference is not significant (female:  $0.70947 \pm 0.00049$ ,  $1\sigma$ ,  $n = 14$ ; male:  $0.70906 \pm 0.00052$ ,  $1\sigma$ ,  $n = 8$ ;  $p = 0.088$ ). With the exception of a single child, children show a relatively narrow strontium isotope composition and strontium concentration range. There are also no significant differences between age groups (infans:  $0.70932 \pm 0.00054$ ,  $1\sigma$ ,  $n = 7$ ; young adult:  $0.70919 \pm 0.00017$ ,  $1\sigma$ ,  $n = 6$ ; adult:  $0.70931 \pm 0.00055$ ,  $1\sigma$ ,  $n = 12$ ; old adult:  $0.70949 \pm 0.00073$ ,  $1\sigma$ ,  $n = 5$ ) but the graphs indicate that, with the exception of one individual with noticeably low  $^{87}\text{Sr}/^{86}\text{Sr}$  values, four older females have higher  $^{87}\text{Sr}/^{86}\text{Sr}$  values than the other individuals. Minor patterning is visible in the strontium isotopic composition of human groups when examined according to time period. Individuals from the earliest graves or the late 5<sup>th</sup> and the early 6<sup>th</sup> century are spread over the entire range of values. However, the most radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  value represents a grave from the earliest period. Furthermore, graves of this time period do not present  $^{87}\text{Sr}/^{86}\text{Sr}$  values lower than 0.70850. These low values only appear in later graves, from the middle of the 6<sup>th</sup> century (Fig. 5.3 A–E).



**Fig. 5.3. Sr ppm and  $^{87}\text{Sr}/^{86}\text{Sr}$  Bockenheim.**

#### 5.1.4 Dirmstein

The strontium isotope ratios and concentrations of 42 tooth enamel samples from 25 individuals from the cemetery of Dirmstein were determined. The results are presented in Fig. 5.4, Fig. 5.5 and Tab. 5.1. For ten individuals only one tooth was analysed, for 13 individuals two teeth were analysed, and for two individuals three teeth were analysed. The  $^{87}\text{Sr}/^{86}\text{Sr}$  values exhibit a large variability ranging from 0.70888 to 0.72938 with a mean of  $0.71125 \pm 0.0042$  ( $1\sigma$ ). The samples are not normally distributed ( $p = 0.000$ ) and have a strong skewness toward more radiogenic values, with outliers having signatures higher than 0.71050 (see appendix Fig. 10.4). The samples with these radiogenic values include only adult individuals from both sexes (2 female, 3 male, 1 unknown) and both time periods (SD-phases 5 and 6). Children and young adults (including juveniles) from both time periods show a relatively restricted range of  $^{87}\text{Sr}/^{86}\text{Sr}$  values roughly between 0.70950 and 0.71020. Most of the remaining adult and old adult individuals are also within this range, with the exception of three male individuals of the SD-phase 5 with slightly lower values below 0.70950 (graves 26, 255, 47). The difference between measured  $^{87}\text{Sr}/^{86}\text{Sr}$  values of teeth from a single individual rang between 0.00005 and 0.01285. For eight individuals the difference was lower than 0.0002 while for seven individuals the differences was larger than 0.00022. The strontium concentrations are between 36 and 286 ppm with a mean of  $116 \pm 44$  ppm ( $1\sigma$ ). Most of the values are clustered between 50 and 150 ppm. One sample, the M2 from grave 24, has a remarkably high strontium concentration of 286 ppm. The M3 of the same individual has the same  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio but a strontium concentration of only 104 ppm. In order to evaluate diagenetic contamination, the P2 was additionally analysed. The P2 has almost the same values as the M3 in both strontium concentration and  $^{87}\text{Sr}/^{86}\text{Sr}$ , indicating that the M2 most probably contained additional strontium from the burial soil. Three teeth from the individual from grave 239 were also analysed. They all show almost the same strontium concentration and composition.



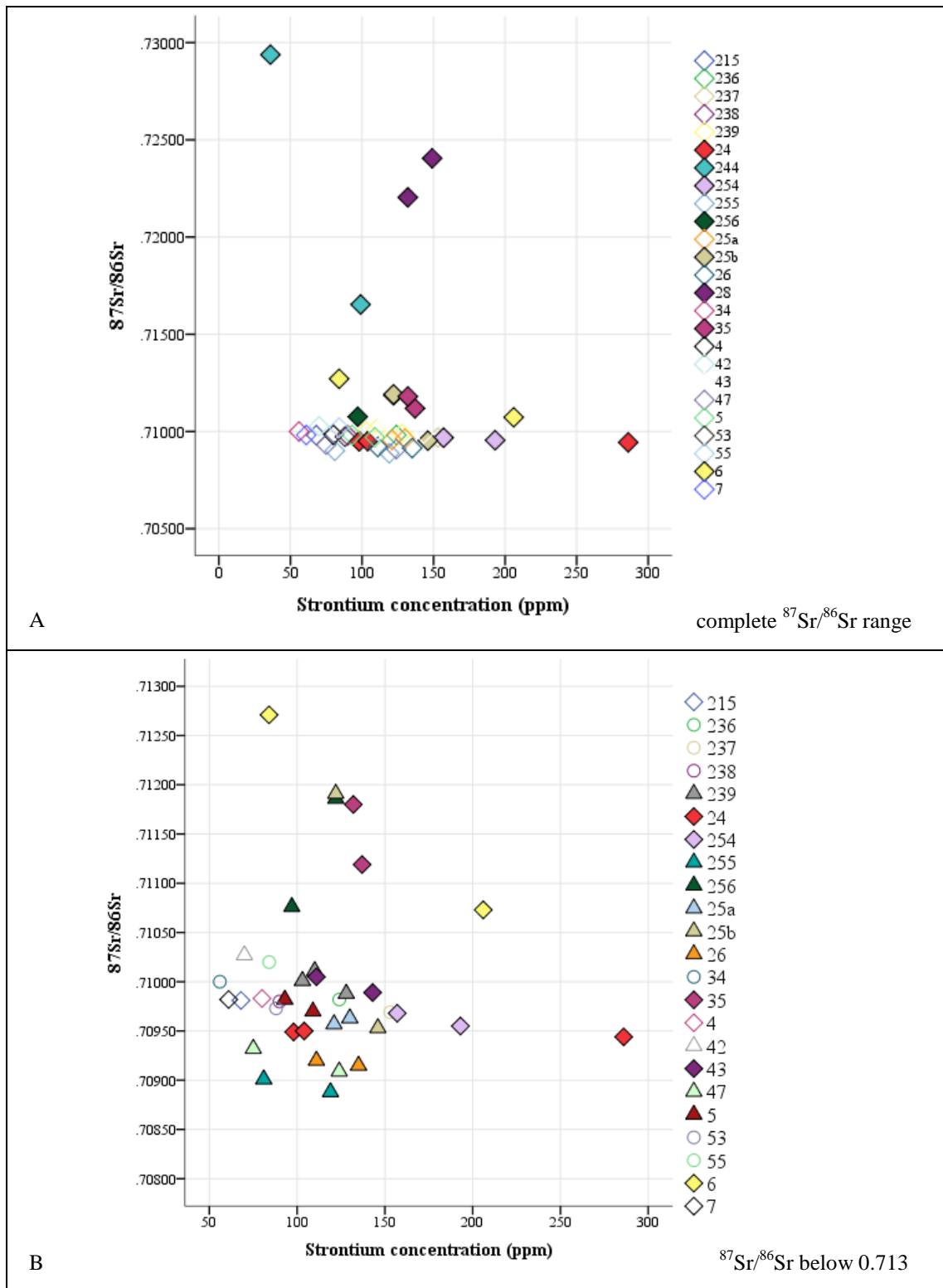


Fig. 5.4. Scatter plot Sr ppm against  $^{87}\text{Sr}/^{86}\text{Sr}$  human enamel Dirmstein.

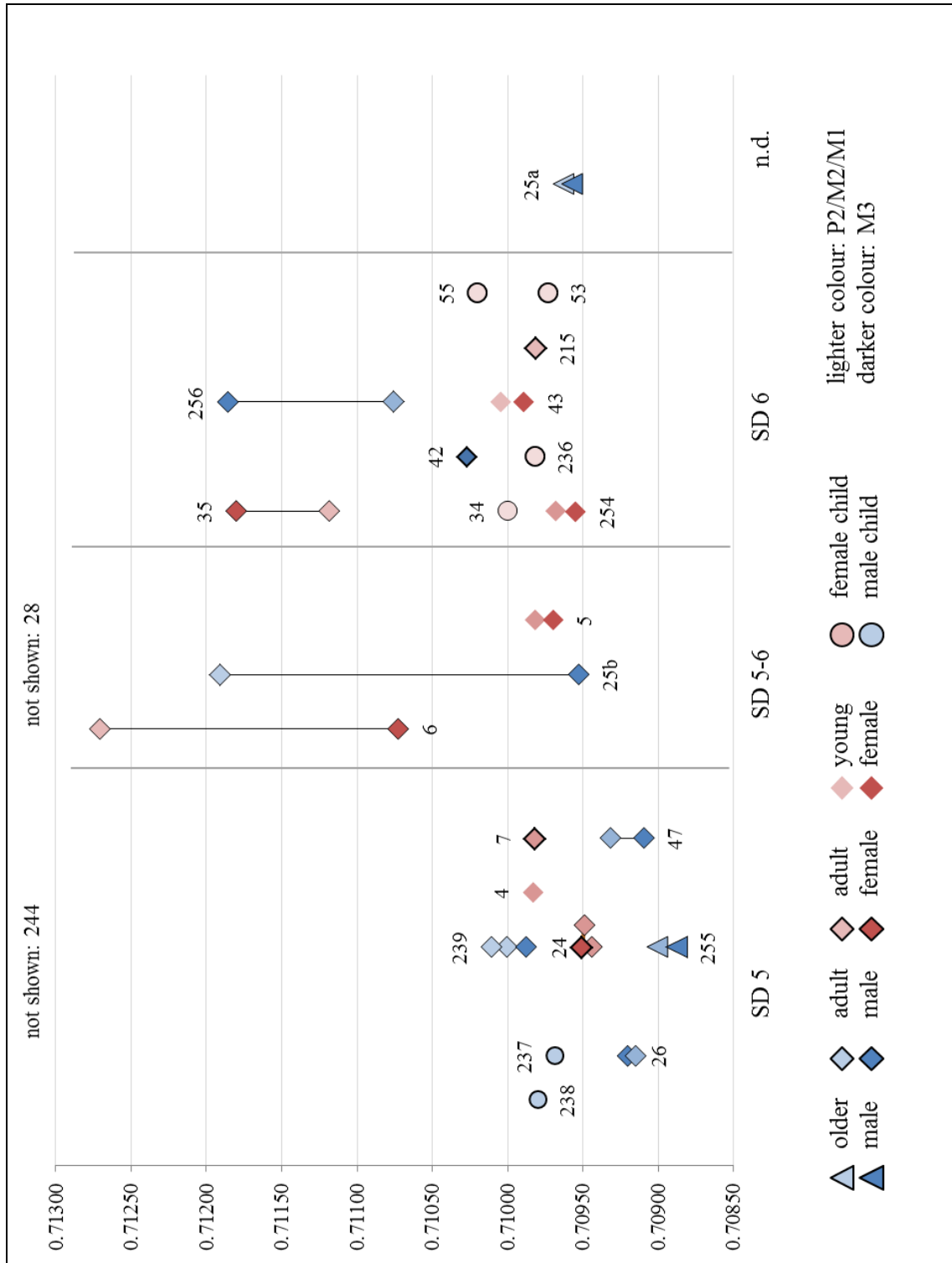


Fig. 5.5.  $^{87}\text{Sr}/^{86}\text{Sr}$  human enamel samples Dirmstein.

## 5.2 Data for the local strontium range

The results of the strontium ratios and concentrations of all samples which were analysed in order to characterise the biologically available strontium signature of the Upper Rhine Valley and the different sites are summarised in Tab. 5.3. A total of 98 samples were measured, including archaeological and modern faunal enamel, archaeological faunal and human dentine, archaeological eggshells, plus soil and water samples. Additionally, human enamel  $^{87}\text{Sr}/^{86}\text{Sr}$  values were used to determine the local strontium range.

**Tab. 5.3. Sr concentrations and  $^{87}\text{Sr}/^{86}\text{Sr}$  values for samples used for the local Sr range.**

Site	Sample /Grave	Material	Species	Tooth	$^{87}\text{Sr}/^{86}\text{Sr}$	Sr conc.
Isenach-E	No.1	Water	-	-	0.71010	604 µg/L
Isenach-U	No.2	Water	-	-	0.71068	458 µg/L
Isenachweiher	No.3	Water	-	-	0.71315	47 µg/L
Eckbach-W	No.4	Water	-	-	0.71019	96 µg/L
Eckbach-K	No.5	Water	-	-	0.71003	209 µg/L
Floßbach-D	No.6	Water	-	-	0.71040	366 µg/L
Eckbach-G	No.7	Water	-	-	0.71022	318 µg/L
Kindenbach-K	No.8	Water	-	-	0.70966	798 µg/L
Pfrimm-P	No.9	Water	-	-	0.70994	613 µg/L
Drachenfels	R1	Enamel	Roe deer	-	0.71351	64 ppm
Drachenfels	R2	Enamel	Roe deer	-	0.71144	176 ppm
Drachenfels	R3	Enamel	Roe deer	-	0.71376	63 ppm
Bockenheim	22	Enamel	Cattle	M2-bulk	0.70989	178 ppm
Bockenheim	195	Enamel	Cattle	M2-bulk	0.70975	314 ppm
Bockenheim	181	Enamel	Cattle	M3-bulk	0.70976	179 ppm
Bockenheim	274	Enamel	Cattle	M3-bulk	0.71107	115 ppm
Dirmstein	148a	Enamel	Cattle	M-bulk	0.71022	170 ppm
Dirmstein	263	Enamel	Cattle	M2-bulk	0.70953	324 ppm
Dirmstein	263	Enamel	Cattle	M2-cusp	0.70964	409 ppm
Dirmstein	263	Enamel	Cattle	M2-mid	0.70954	325 ppm
Dirmstein	263	Enamel	Cattle	M2-cervix	0.70981	375 ppm
Eppstein	269	Enamel	Cattle	P-bulk	0.70953	293 ppm
Eppstein	358	Enamel	Cattle	M1-bulk	0.70876	231 ppm
Eppstein	358	Enamel	Cattle	M1-cusp	0.70877	257 ppm
Eppstein	358	Enamel	Cattle	M1-cervix	0.70877	219 ppm
Bockenheim	261	Enamel	Pig	I	0.70982	160 ppm
Bockenheim	311	Enamel	Pig	M2	0.70985	178 ppm
Dirmstein	106	Enamel	Pig	C	0.70942	207 ppm
Dirmstein	230	Enamel	Pig	M2	0.71041	264 ppm
Eppstein	11	Enamel	Pig	M2	0.70923	335 ppm
Eppstein	249	Enamel	Pig	M3-bulk	0.70969	256 ppm
Eppstein	270	Enamel	Pig	I-cusp	0.71160	197 ppm

## RESULTS

Eppstein	270	Enamel	Pig	I-cervix	0.70993	198 ppm
Eppstein	270	Enamel	Pig	I-bulk	0.71042	142 ppm
Dirmstein	234	Enamel	Horse	M-bulk	0.70905	604 ppm
Dirmstein	234	Enamel	Horse	M-cusp	0.70809	767 ppm
Dirmstein	234	Enamel	Horse	M-mid	0.70872	640 ppm
Dirmstein	234	Enamel	Horse	M-cervix	0.71076	442 ppm
Eppstein	15	Enamel	Horse	M2	0.70983	575 ppm
Bockenheim	533	Enamel	Sheep/goat	M2	0.70967	389 ppm
Dirmstein	112	Enamel	Sheep/goat	M1-bulk	0.70856	183 ppm
Eppstein	358	Enamel	Sheep/goat	M2s	0.70955	372 ppm
Bockenheim	363	Enamel	Canid	M2	0.70916	380 ppm
Dirmstein	39	Enamel	Canid	C-bulk	0.70990	403 ppm
Bockenheim	342	Eggshell	Chicken	-	0.70985	430 ppm
Bockenheim	451	Eggshell	Chicken	-	0.70986	517 ppm
Bockenheim	479	Eggshell	Duck/goose	-	0.70912	392 ppm
Bockenheim	485	Eggshell	Chicken	-	0.70957	348 ppm
Bockenheim	509	Eggshell	?	-	0.70884	802 ppm
Dirmstein	24	Eggshell	Chicken	-	0.71000	541 ppm
Dirmstein	35	Eggshell	Chicken	-	0.70994	662 ppm
Eppstein	217	Eggshell	Chicken	-	0.70936	468 ppm
Eppstein	222	Eggshell	duck/goose	-	0.70943	368 ppm
Eppstein	236	Eggshell	Chicken	-	0.70934	471 ppm
Eppstein	255	Eggshell	Duck/goose	-	0.70931	274 ppm
Eppstein	292	Eggshell	Chicken	-	0.70942	331 ppm
Eppstein	411	Eggshell	Chicken	-	0.70948	844 ppm
Eppstein	422	Eggshell	Chicken	-	0.70969	909 ppm
Bockenheim	135	Soil	-	-	0.71323	147 ppm
Bockenheim	181	Soil	-	-	0.71381	141 ppm
Dirmstein	170	Soil	-	-	0.71601	111 ppm
Dirmstein	226	Soil	-	-	0.71490	51 ppm
Eppstein	52	Soil	-	-	0.71266	322 ppm
Bockenheim	181	Dentine	Cattle	M3	0.70971	463 ppm
Bockenheim	195	Dentine	Cattle	M2	0.70971	544 ppm
Bockenheim	274	Dentine	Cattle	M3	0.70970	499 ppm
Dirmstein	148a	Dentine	Cattle	M	0.70991	550 ppm
Dirmstein	263	Dentine	Cattle	M2	0.70983	513 ppm
Eppstein	358	Dentine	Cattle	M1	0.70916	581 ppm
Bockenheim	261	Dentine	Pig	Ii	0.70989	531 ppm
Dirmstein	106	Dentine	Pig	Ci	0.70978	540 ppm
Dirmstein	230	Dentine	Pig	M2	0.71007	1164 ppm
Eppstein	249	Dentine	Pig	M3	0.70947	494 ppm
Eppstein	270	Dentine	Pig	I	0.70964	408 ppm
Dirmstein	234	Dentine	Horse	M	0.70997	617 ppm
Eppstein	15	Dentine	Horse	M2	0.70957	830 ppm
Dirmstein	112	Dentine	Sheep/goat	M1	0.70943	461 ppm
Dirmstein	39	Dentine	Canid	C	0.70994	1273 ppm
Bockenheim	22	Dentine	Human	M2	0.70945	245 ppm

Bockenheim	391	Dentine	Human	M2	0.70941	170 ppm
Bockenheim	392	Dentine	Human	M2	0.70952	50 ppm
Bockenheim	454	Dentine	Human	M1	0.70949	331 ppm
Bockenheim	488	Dentine	Human	M2	0.70933	377 ppm
Dirmstein	5	Dentine	Human	M2	0.71001	274 ppm
Dirmstein	35	Dentine	Human	M1?	0.71018	363 ppm
Dirmstein	42	Dentine	Human	M2	0.71003	249 ppm
Dirmstein	43	Dentine	Human	M2	0.71008	692 ppm
Dirmstein	47	Dentine	Human	M2	0.70965	245 ppm
Dirmstein	215	Dentine	Human	M2	0.70987	462 ppm
Dirmstein	244	Dentine	Human	M2	0.71208	222 ppm
Dirmstein	256	Dentine	Human	M2	0.71034	254 ppm
Eppstein	3	Dentine	Human	M2	0.70940	403 ppm
Eppstein	38	Dentine	Human	M2	0.70923	288 ppm
Eppstein	50	Dentine	Human	M3?	0.70863	292 ppm
Eppstein	71	Dentine	Human	M2	0.70944	443 ppm
Eppstein	189	Dentine	Human	M1	0.70933	270 ppm
Eppstein	198	Dentine	Human	M2	0.70935	339 ppm
Eppstein	246	Dentine	Human	M2	0.70940	266 ppm
Eppstein	426	Dentine	Human	P2	0.70965	292 ppm

### 5.2.1 Water samples

A total of nine water samples were analysed. The results are presented in Tab. 5.3, Fig. 5.6 and Fig. 5.7. The water samples show a total  $^{87}\text{Sr}/^{86}\text{Sr}$  range between 0.70966 and 0.71314 (mean  $0.71049 \pm 0.00104$ ) and strontium concentrations of 47 to 798  $\mu\text{g}/\text{L}$  (mean  $390 \pm 252 \mu\text{g}/\text{L}$ ). The lowest strontium signatures are found in the two northernmost streams in the area of the site of Bockenheim, with 0.70966 for the Kindenbach (no.8) and 0.70994 for the Pfrimm stream (no.9). Both sample locations also had the highest strontium concentrations. The  $^{87}\text{Sr}/^{86}\text{Sr}$  values for the three samples from the Eckbach stream that runs through the site of Dirmstein (no.4, 5, and 7) are very similar, between 0.71003 and 0.71022. The strontium concentrations increase from 96-209  $\mu\text{g}/\text{L}$  from the sample location in the Buntsandstein area (no. 4 and no.5 respectively) to 318  $\mu\text{g}/\text{L}$  in the Rhine Valley (no.7) but the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios do not decrease. Indeed, the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio on Quaternary/Pliocene sediments (no.7) is the most radiogenic. The sample from the Floßbach (no.6), the second stream that runs through Dirmstein, is slightly increased; with 0.71040 in comparison to the samples from the Eckbach. This applies also for the strontium concentration of 366  $\mu\text{g}/\text{L}$ . The most southern stream, the Isenach, clearly shows a decreasing tendency of

$^{87}\text{Sr}/^{86}\text{Sr}$  values from the sample location in the Buntsandstein area (no.3), to the sample taken on Tertiary sediments (no.2), to the last location in the proximity of Eppstein on Tertiary/Pliocene sediments (no.1). In comparison, the strontium concentrations show an increasing trend.

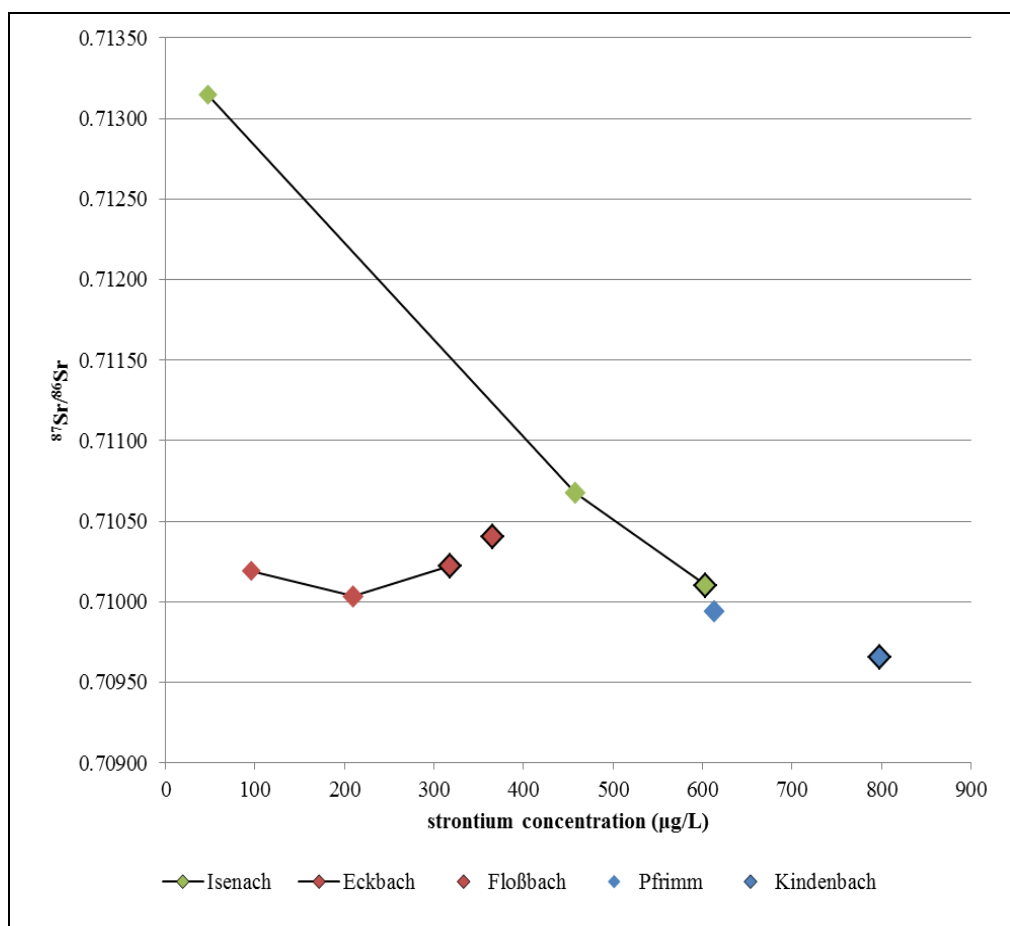


Fig. 5.6. Scatter plot  $^{87}\text{Sr}/^{86}\text{Sr}$  versus concentration for the stream water samples.

### 5.2.2 Modern deer samples

The three modern deer tooth enamel samples show  $^{87}\text{Sr}/^{86}\text{Sr}$  values between 0.71144 and 0.71376, with concentrations ranging from 63 to 176 ppm. Two individuals (R1, R3) show nearly the same  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio, above 0.71300, and strontium concentration of around 63 ppm while the third individual (R2) has a lower  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of around 0.71100 and a concentration of 176 ppm (see Tab. 5.3 and Fig. 5.7).

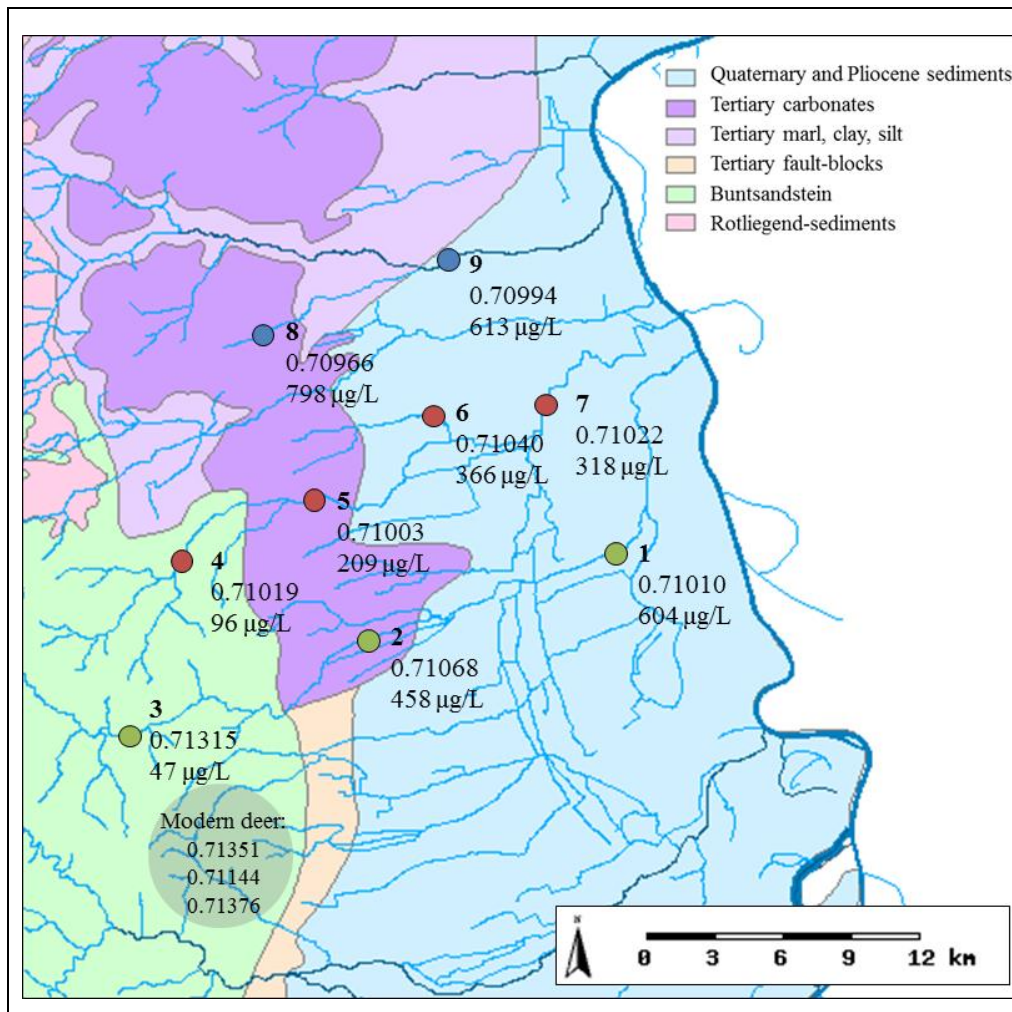


Fig. 5.7.  $^{87}\text{Sr}/^{86}\text{Sr}$  ranges, concentrations and location of water and deer samples (map: Geoexplorer of the Rhineland-Palatinate Water Management<sup>18</sup>).

### 5.2.3 Soil samples

A total of five soil samples were analysed. The  $^{87}\text{Sr}/^{86}\text{Sr}$  values range between 0.71266 and 0.71601 and the concentrations are between 51 and 322 ppm. Soil samples from Dirmstein are the most radiogenic, followed by Bockenheim, with the lowest value coming from the Eppstein sample (Tab. 5.3, Fig. 5.8).

<sup>18</sup> [http://www.geoexplorer-wasser.rlp.de/geoexplorer/application/geoportal/geoexplorer.jsp?property\\_name=geoportal](http://www.geoexplorer-wasser.rlp.de/geoexplorer/application/geoportal/geoexplorer.jsp?property_name=geoportal) (10.01.2014).

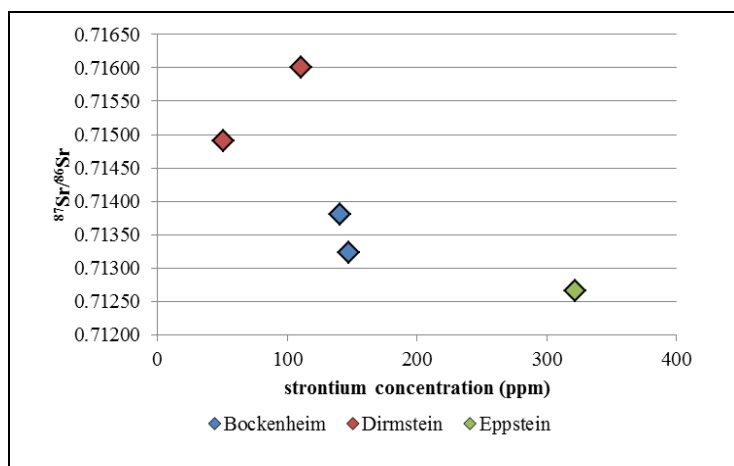


Fig. 5.8. Scatter plot  $^{87}\text{Sr}/^{86}\text{Sr}$  versus Sr ppm soil samples.

#### 5.2.4 Archaeological faunal material

The complete sample set has an  $^{87}\text{Sr}/^{86}\text{Sr}$  range from 0.70809 to 0.71160 with a mean of  $0.70965 \pm 0.00073$  ( $1\sigma$ ). The strontium concentrations range between 115 and 767 ppm with a mean of  $315 \pm 157$  ppm ( $1\sigma$ ) (see Tab. 5.3 and Fig. 5.9).

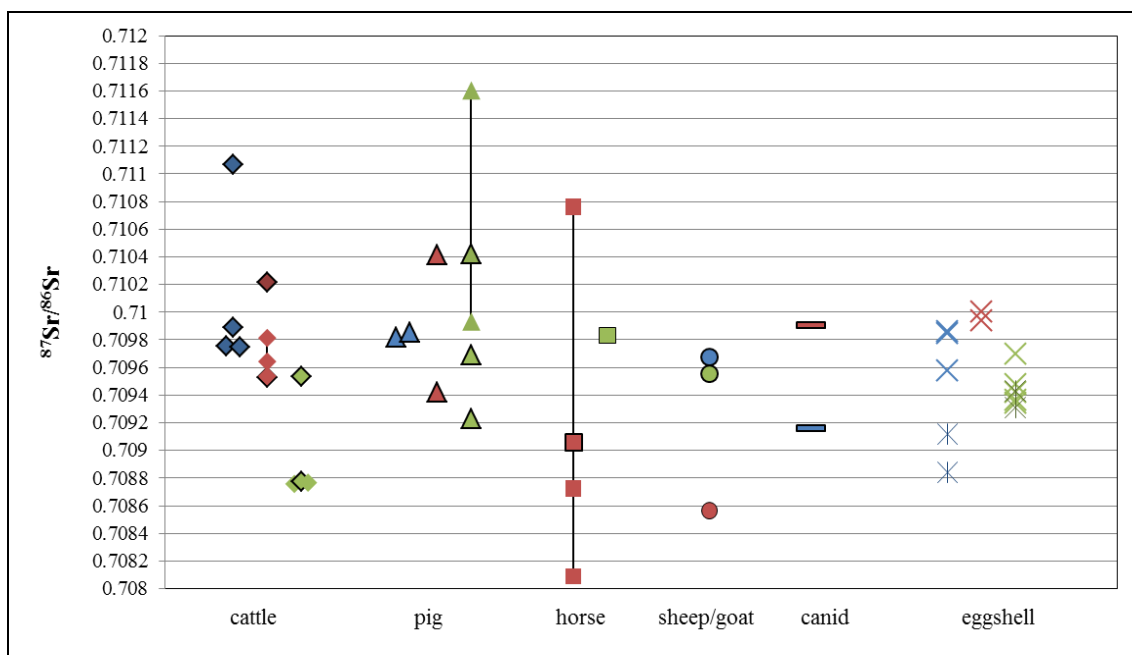


Fig. 5.9.  $^{87}\text{Sr}/^{86}\text{Sr}$  of archaeological faunal material (blue = Bockenheim; red = Dirmstein; green = Eppstein).

The  $^{87}\text{Sr}/^{86}\text{Sr}$  values of the cattle samples range between 0.70876 and 0.71107 (13 measurements from eight individuals). Most of the values cluster between 0.70950 and 0.71022 (nine measurements from six individuals), which encompasses individuals from each cemetery. The strontium concentrations of all cattle samples



have a span between 115 to 409 ppm with a mean of  $261 \pm 88$  ppm ( $1\sigma$ ,  $n = 13$ ). The  $^{87}\text{Sr}/^{86}\text{Sr}$  of pig tooth enamel samples range between 0.70923 and 0.71160 (nine measurements from seven individuals). Most of the samples cluster between 0.70923 and 0.71042 with the exception of one cusp sample from a pig from Eppstein. The sample from the cervix has a value of 0.70993 and the bulk sample of 0.71042. The strontium concentrations range from 142 to 335 ppm with a mean of  $215 \pm 60$  ppm ( $1\sigma$ ,  $n = 9$ ). The sheep/goat tooth enamel samples ( $n = 3$ ) range between 0.70856 and 0.70967 and have strontium concentrations between 183 and 389 ppm. The horse tooth from Dirmstein was measured sequentially and shows a wide range of  $^{87}\text{Sr}/^{86}\text{Sr}$  values between 0.70809 and 0.71076 and high strontium concentrations between 442 and 767 ppm. The Eppstein horse tooth was only measured once (bulk) and has a value of 0.70983 and a strontium concentration of 575 ppm. The samples from two canidae, one from Dirmstein and the other from Bockenheim, have values between 0.70916 and 0.70990 and strontium concentrations of 380 and 403 ppm. A total of 14 eggshell samples from the three sites were analysed.  $^{87}\text{Sr}/^{86}\text{Sr}$  ranges from 0.70884 to 0.7100 with a mean of  $0.70952 \pm 0.00032$ . The strontium concentrations are between 274 and 909 ppm with a mean of  $525 \pm 203$  ppm. The eggshell samples from the Dirmstein cemetery show the highest values around 0.71000. The samples from Eppstein have a narrow range between 0.70930 and 0.70970. The eggshell samples from Bockenheim show the highest variability. The lowest values are from a different bird species than the domestic chicken.

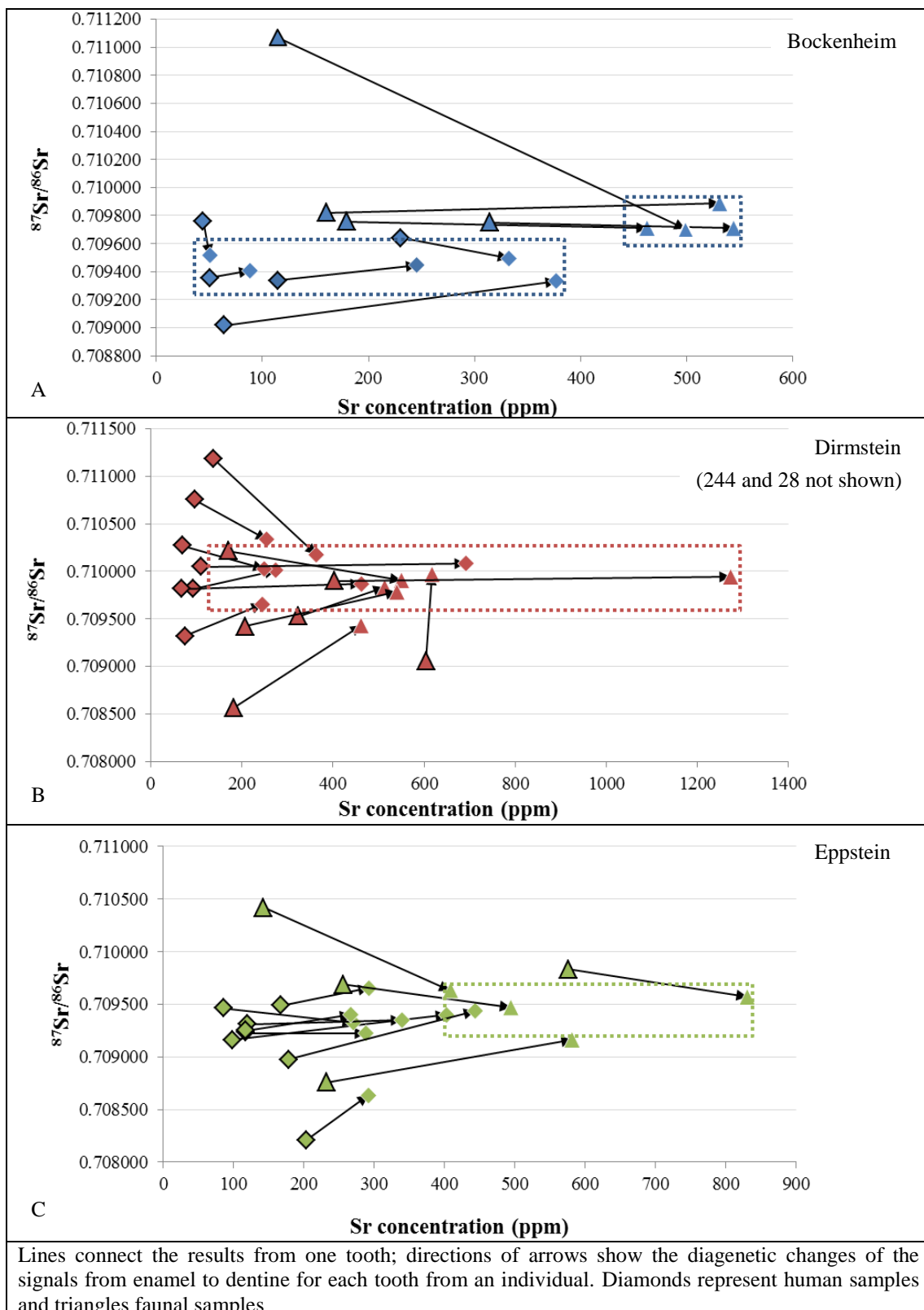
### 5.2.5 Human and faunal dentine

A total of 36 randomly selected human and faunal dentine samples from all the cemeteries were analysed in order to estimate the local strontium range of each site. The complete sample set has a strontium isotopic range from 0.70863 to 0.71208 with a mean of  $0.70970 \pm 0.00053$  ( $1\sigma$ ). The strontium concentrations show a span between 50 and 127 ppm. The mean strontium concentration for the faunal dentine samples ( $631 \pm 257$  ppm) is higher than for the human dentine samples ( $308 \pm 123$  ppm). All dentine samples have elevated strontium concentrations in comparison to the enamel strontium concentrations. The  $^{87}\text{Sr}/^{86}\text{Sr}$  range for the human samples lies between 0.70863 and 0.71208 (mean  $0.71208 \pm 0.00066$ ) and for the faunal samples between 0.70916 and 0.71007 ( $0.70972 \pm 0.00024$ ). There are slight differences in

dentine  $^{87}\text{Sr}/^{86}\text{Sr}$  values between the three cemeteries. Plots of  $^{87}\text{Sr}/^{86}\text{Sr}$  and strontium concentrations of human and faunal paired enamel and dentine samples are shown in Fig. 5.10A–C.

The  $^{87}\text{Sr}/^{86}\text{Sr}$  values of the ten dentine samples from the cemetery Bockenheim range between 0.70925 and 0.70989 with a mean of  $0.70955 \pm 0.00020$  ( $1\sigma$ ). The strontium concentrations have values between 50 and 544 ppm (mean  $347 \pm 166$  ppm,  $1\sigma$ ). Fig. 5.10A shows that the diagenetic vectors of the human and faunal samples converge on slightly different values. Faunal dentine samples converge on  $^{87}\text{Sr}/^{86}\text{Sr}$  values in the region of 0.70980 (mean  $0.70975 \pm 0.00009$ ) while the human dentine samples converge on  $^{87}\text{Sr}/^{86}\text{Sr}$  values in the region of 0.70940 (mean  $0.70941 \pm 0.00010$ ). The strontium concentrations are also higher for the faunal samples (mean  $509 \pm 35$ ) in comparison to the human samples (mean  $238 \pm 117$ ). The  $^{87}\text{Sr}/^{86}\text{Sr}$  range for the 15 dentine samples which were sampled from the cemetery at Dirmstein is between 0.70943 and 0.71208 (mean  $0.71008 \pm 0.00060$ ,  $1\sigma$ ) and the strontium concentrations are between 223 to 1273 ppm (mean  $525 \pm 319$  ppm,  $1\sigma$ ). The mean  $^{87}\text{Sr}/^{86}\text{Sr}$  values for the human dentine samples (mean  $0.71029 \pm 0.00076$ ,  $n = 8$ ) are higher than the values of the faunal samples (mean  $0.70955 \pm 0.00021$ ,  $n = 7$ ) while the strontium concentrations are higher for the faunal samples (mean  $731 \pm 337$  ppm) in comparison to the human strontium concentrations (mean  $324 \pm 70$  ppm). Fig. 5.10B shows that the diagenetic vectors of the human and faunal samples from this site converge on  $^{87}\text{Sr}/^{86}\text{Sr}$  values in the region of 0.70100.

The strontium isotope range of the Eppstein samples is between 0.70863 and 0.70965 (mean  $0.70936 \pm 0.00027$ ,  $1\sigma$ ,  $n = 12$ ) and the strontium concentrations are between 266 to 830 ppm (mean  $409 \pm 166$  ppm,  $1\sigma$ ,  $n = 12$ ). The mean  $^{87}\text{Sr}/^{86}\text{Sr}$  values for the human dentine samples (mean  $0.70930 \pm 0.00030$ ,  $n = 8$ ) are slightly lower than the values of the faunal samples (mean  $0.70946 \pm 0.00021$ ,  $n = 4$ ). The strontium concentrations are also higher for the faunal samples (mean  $578 \pm 182$  ppm) in comparison to the human strontium concentrations (mean  $345 \pm 161$  ppm). Fig. 5.10C shows that the diagenetic vectors of the human and faunal samples converge on  $^{87}\text{Sr}/^{86}\text{Sr}$  values in the region of 0.7095.



**Fig. 5.10.** Plot of  $^{87}\text{Sr}/^{86}\text{Sr}$  and Sr ppm of paired enamel-dentine samples for each cemetery.

### 5.2.6 Approaches based on archaeological human enamel

The  $^{87}\text{Sr}/^{86}\text{Sr}$  values of children from all three cemeteries range from 0.70820 to 0.71020 with a mean of  $0.70953 \pm 0.00037$  ( $n = 25$ ;  $1\sigma$ ). Excluding the two outliers below 0.70928, the range is between 0.70928 and 0.71020 with a mean of  $0.70961 \pm 0.00023$  ( $n = 23$ ;  $1\sigma$ ). The local range based on the mean  $\pm 2\text{SD}$  is 0.70915 to 0.71006. There are slight differences in the mean  $^{87}\text{Sr}/^{86}\text{Sr}$  values of children between the different cemeteries. Children from Bockenheim have the lowest mean  $^{87}\text{Sr}/^{86}\text{Sr}$  value with  $0.70951 \pm 0.00024$  ( $1\sigma$ ) (mean  $\pm 2\text{SD}$ : 0.70904–0.70998,  $n = 6$ ; excluding 1 outlier), followed by Eppstein with mean  $^{87}\text{Sr}/^{86}\text{Sr}$  values of  $0.70952 \pm 0.00010$  ( $1\sigma$ ) (mean  $\pm 2\text{SD}$ : 0.70932–0.70972,  $n = 11$ , excluding 1 outlier). The highest mean  $^{87}\text{Sr}/^{86}\text{Sr}$  values are in Dirmstein with  $0.70987 \pm 0.00019$  ( $1\sigma$ ) (mean  $\pm 2\text{SD}$ : 0.70949–0.71026,  $n = 6$ ) (Fig. 5.11)

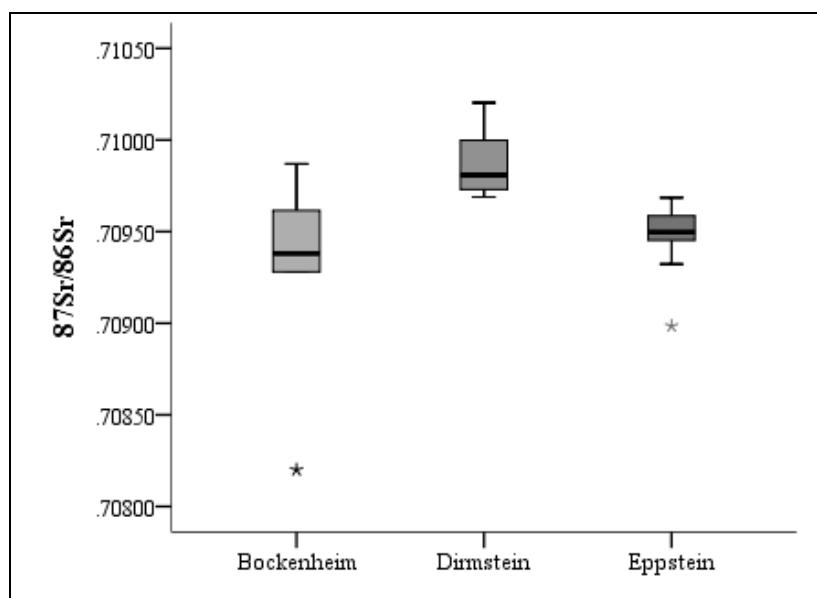
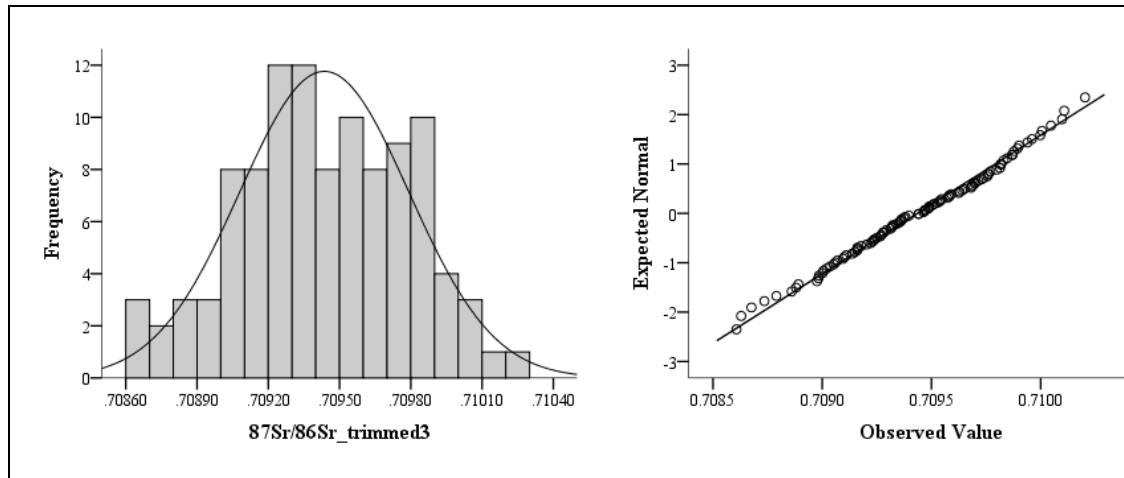


Fig. 5.11. Box plots showing  $^{87}\text{Sr}/^{86}\text{Sr}$  of non-adult individuals from each site.

For large sample sets it is also possible to use a statistical approach for the definition of the local strontium range (Wright 2005). The approach is based on the assumption that people which are consuming local water and food have  $^{87}\text{Sr}/^{86}\text{Sr}$  values which follow a normal distribution. Individuals that contribute to a non-normal distribution of the data can be identified as outliers. From the complete data set of the human tooth enamel samples, outliers were stepwise removed, until an approximate normal distribution was achieved. The best fit was achieved with the third trimmed data set (Fig. 5.12 and appendix Fig. 10.6). The biologically available

$^{87}\text{Sr}/^{86}\text{Sr}$  signature after this statistical approach is between 0.70861 and 0.71020 with a mean of  $0.70944 \pm 0.00003$   $1\sigma$  ( $n = 105$ ).



**Fig. 5.12.** Graphical description of the best fit data set with a normal distribution.

Another approach arranges all human enamel  $^{87}\text{Sr}/^{86}\text{Sr}$  values in ascending order and calculates the difference between each succeeding sample to detect sudden breaks which may mark the border between locals and non-locals (Tung/Knudson 2011). When doing this for the complete human enamel sample set, samples from 0.70898 to 0.71011 ( $n = 96$ ) have a maximum difference of 0.00004 between each other. Between 0.70889 and 0.70898 as well as between 0.71011 and 0.71020 are the first larger breaks with a difference of 0.00009. For Eppstein, individuals ( $n = 40$ ) between 0.70898 and 0.70976 show differences between each other at a maximum of 0.00006. Sudden breaks of 0.00009 also occur between 0.70889 and 0.70898, as well as between 0.70985 and 0.70976. In Bockenheim, the range with low differences (maximum 0.00008) between the samples is from 0.70902 to 0.70947 ( $n = 14$ ). There is a break of 0.00016 between 0.70886 and 0.70902, and between 0.70947 and 0.70958 with a difference of 0.00011. Samples between 0.70958 and 0.70977 ( $n = 7$ ) show also few differences between each other and therefore it may be the case that it is rather the break of 0.000010 between 0.70988 and 0.70987 which is the border between local or non-local. However, the largest break of 0.00038 is between 0.70994 and the most radiogenic samples of Bockenheim with a value of 0.71032. In Dirmstein, between 0.70944 and 0.70989 ( $n = 18$ ), there are only low differences between the samples, at a maximum of 0.00007. Larger shifts are between 0.70989 and 0.71000 (0.00010) as well as between 0.70932 and 0.70944 (0.00012).

## 6 Oxygen and carbon isotope analysis

### 6.1 Pretreatment experiments

#### 6.1.1 Pretreatment experiment I

Results of the pretreatment experiment I are summarised in Tab. 6.1. The most obvious change is that drying the samples at 60°C causes a decrease of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values. The decrease of  $\delta^{18}\text{O}$  for the modern tooth is only 0.09‰ on average for all measurements, while it is 0.67‰ on average for all samples of the ancient tooth. For  $\delta^{13}\text{C}$  the difference is 0.22‰ for the modern and 0.28‰ for the ancient tooth. The differences between the treatments show no clear patterns either for  $\delta^{18}\text{O}$  or for  $\delta^{13}\text{C}$ . The differences in  $\delta^{18}\text{O}$  are less than 0.13‰ for the air-dried and less than 0.06‰ for the 60°C dried modern tooth. For the ancient tooth, the differences in  $\delta^{18}\text{O}$  are less than 0.10‰ for the air-dried and less than 0.06‰ for the 60°C dried tooth. The  $\delta^{13}\text{C}$  difference is 0.11‰ for the modern air-dried and less than 0.07‰ for the 60°C dried modern tooth. For the ancient tooth, the difference between the protocols for the air-dried tooth is less than 0.14‰ and less than 0.12‰ for the 60°C dried tooth.

In conclusion, the different pretreatments of the samples had no obvious effect on the  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values of either the modern or the ancient tooth. However, it has been detected that the drying of the samples at 60°C resulted in decreased  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values for both the ancient and the modern tooth.

**Tab. 6.1. Results pretreatment experiment I.**

Drying	1st step	2nd step	$\delta^{13}\text{C}$	$\pm$	$\delta^{18}\text{O}$	$\pm$	$\Delta\delta^{13}\text{C}$	$\Delta\delta^{18}\text{O}$	$\Delta\delta^{13}\text{C}$	$\Delta\delta^{18}\text{O}$
Air	Untreated	Untreated	-13.82	0.15	-5.35	0.07	0.32	0.04		
Air	3% NaOCl 30min	0.1 M acetic acid 10min	-13.9	0.16	-5.28	0.07	0.17	0.06		
Air	3% NaOCl 24h	0.1 M acetic acid 3h	-13.93	0.09	-5.22	0.01	0.17	0.18		
			<b>-13.88</b>	<b>0.06</b>	<b>-5.28</b>	<b>0.07</b>	<b>0.22</b>	<b>0.09</b>	<b>-0.11</b>	<b>-0.13</b>
60°C	Untreated	Untreated	-14.14	0.02	-5.39	0.03				
60°C	3% NaOCl 30min	0.1 M acetic acid 10min	-14.07	0.17	-5.34	0.06				
60°C	3% NaOCl 24h	0.1 M acetic acid 3h	-14.1	0.01	-5.4	0.15				
			<b>-14.10</b>	<b>0.04</b>	<b>-5.38</b>	<b>0.03</b>			<b>-0.07</b>	<b>-0.06</b>
Air	Untreated	Untreated	-13.54	0.14	-4.36	0.1	0.27	0.6		
Air	3% NaOCl 30min	0.1 M acetic acid 10min	-13.52	0.2	-4.3	0.05	0.3	0.66		
Air	3% NaOCl 24h	0.1 M acetic acid 3h	-13.66	0.11	-4.26	0.11	0.27	0.76		
			<b>-13.57</b>	<b>0.08</b>	<b>-4.31</b>	<b>0.05</b>	<b>0.28</b>	<b>0.67</b>	<b>-0.14</b>	<b>-0.10</b>
60°C	Untreated	Untreated	-13.81	0.04	-4.96	0.17				
60°C	3% NaOCl 30min	0.1 M acetic acid 10min	-13.82	0.02	-4.96	0.07				
60°C	3% NaOCl 24h	0.1 M acetic acid 3h	-13.93	0.01	-5.02	0.07				
			<b>-13.85</b>	<b>0.07</b>	<b>-4.98</b>	<b>0.03</b>			<b>-0.12</b>	<b>-0.06</b>

<sup>a</sup>Difference between air dried and 60°C dried sample of the same protocol

<sup>b</sup>Difference between the largest and lowest value between the protocols

### 6.1.2 Pretreatment experiment II

Results of the  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values of the second pretreatment experiment with the early medieval samples are listed in Tab. 10.5. Differences in isotope value among duplicate analyses of the untreated and treated samples were low. For  $\delta^{13}\text{C}$  the values range between 0.0 and 0.3 with a mean of  $0.08 \pm 0.06\text{‰}$  and for  $\delta^{18}\text{O}$  the values range between 0.01 and 0.44 with a mean of  $0.12 \pm 0.09\text{‰}$ .

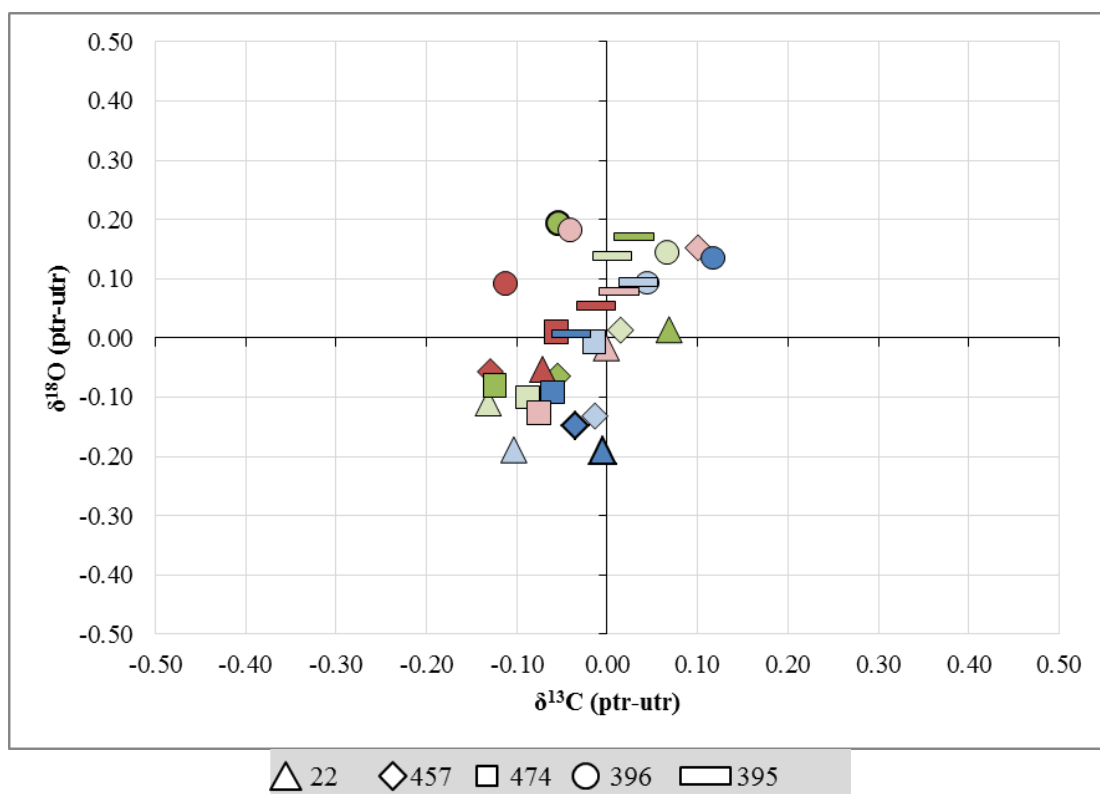
In order to test if drying the samples at  $60^\circ\text{C}$  decreases the  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values as was observed in the first pretreatment experiment, five more samples from Dirmstein were compared (Tab. 6.2). For two sample pairs (no.2 and 4) the  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  were almost identical. For the sample pair no.3 and 5 the  $\delta^{18}\text{O}$  values are also almost identical while the  $\delta^{13}\text{C}$  values for the samples which were dried at  $60^\circ\text{C}$  are increased in comparison to the air-dried samples. For sample no.1 both the  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values between the different pretreatments differ by almost 2‰. The  $\delta^{13}\text{C}$  value is enriched while the  $\delta^{18}\text{O}$  value is decreased. Therefore, no systematic decrease was detected within the samples which were dried at  $60^\circ\text{C}$ . The differing values have other causes than the drying temperature.

**Tab. 6.2. Differences between drying methods.**

No.	Site-Grave-Tooth	No.	Protocol	$\delta^{13}\text{C}$	$\pm$	$\delta^{18}\text{O}$	$\pm$	$\Delta\delta^{13}\text{C}$	$\Delta\delta^{18}\text{O}$
1	Dir-24-M3	A	Untreated (air-dried)	-13.95	0.11	-3.09	0.21	-1.92	1.73
1	Dir-24-M3	AA	Untreated ( $60^\circ\text{C}$ )	-12.04	0.03	-4.82	0.27		
2	Dir-25b-M3	A	Untreated (air-dried)	-12.95	0.16	-4.89	0.26	0.04	-0.02
2	Dir-25b-M3	AA	Untreated ( $60^\circ\text{C}$ )	-12.99	0.08	-4.87	0.23		
3	Dir-26-M3	A	Untreated (air-dried)	-13.03	0.06	-4.66	0.09	-0.23	0.05
3	Dir-26-M3	AA	Untreated ( $60^\circ\text{C}$ )	-12.80	0.03	-4.71	0.14		
4	Dir-47-M3	A	Untreated (air-dried)	-13.70	0.12	-4.52	0.04	0.03	-0.05
4	Dir-47-M3	AA	Untreated ( $60^\circ\text{C}$ )	-13.73	0.10	-4.47	0.06		
5	Dir-244-M3	A	Untreated (air-dried)	-14.40	0.16	-5.69	0.14	-0.52	0.08
5	Dir-244-M3	AA	Untreated ( $60^\circ\text{C}$ )	-13.88	0.03	-5.77	0.22		

To visualise the effect of the different treatments, the isotope differences between the values of the treated samples and the values of untreated samples, calculated by the mean of all untreated samples of one individual (three measurements per sample), are listed in Tab. 10.5 and plotted in Fig. 6.1, Fig. 6.2, and Fig. 6.3. The different symbols correspond to the different individuals from a site. The colours correspond to the colours in Tab. 10.4. The air-dried samples from Dirmstein are excluded.

The differences between the pretreatment protocols for all samples for  $\delta^{13}\text{C}$  range between 0.00‰ and 0.34‰ with a mean of  $0.09 \pm 0.07\text{‰}$  and for  $\delta^{18}\text{O}$  between 0.00‰ and 0.30‰ with a mean of  $0.10 \pm 0.08\text{‰}$ . For the samples from Bockenheim and Eppstein all differences are  $\leq 0.20\text{‰}$ ; only some samples from Dirmstein showed differences  $\geq 0.20\text{‰}$  with the highest values of 0.34‰. These values are partly lower than the difference between double measurements of one sample with the same treatment. Therefore, it can be concluded that the pretreatment of the samples had no visible effect on the  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values of the samples. However, the different scattering pattern of values between the different sites is rather the result of incomplete homogenisation of the samples before treatment or reflects the different states of preservation between the sites.



**Fig. 6.1. Results of pretreatment experiment II for Bockenheim (ptr-utr = pretreated-untreated).**



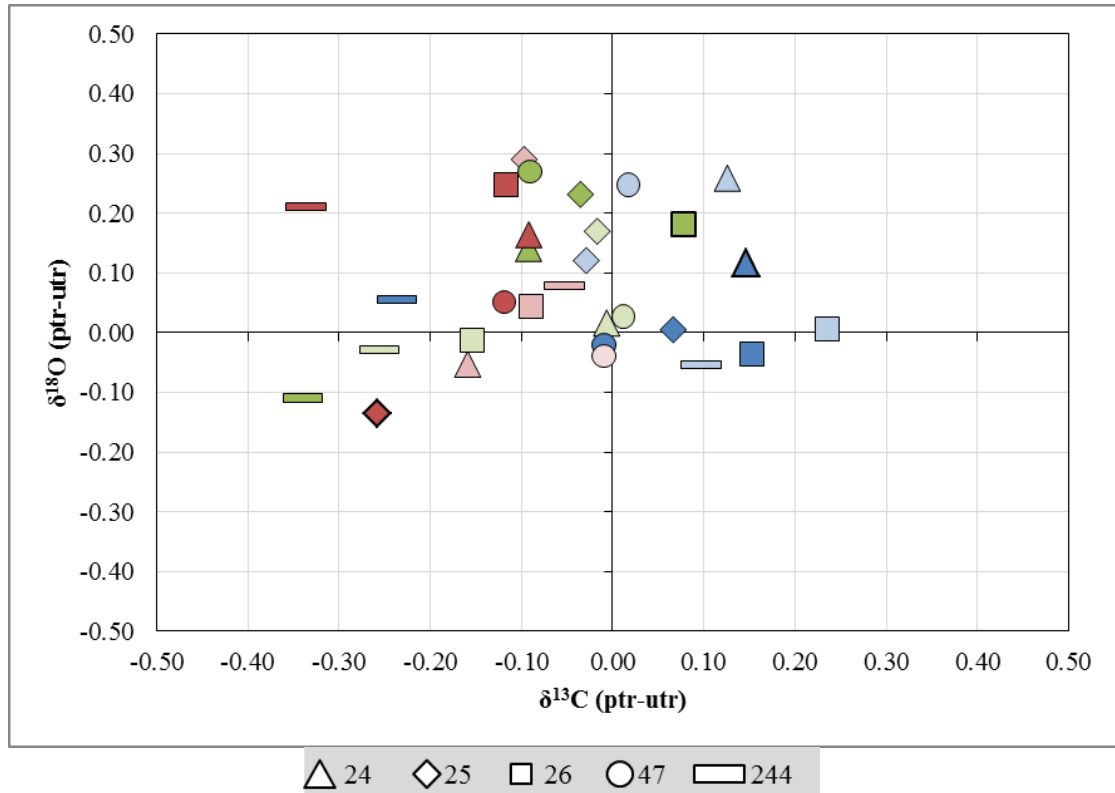


Fig. 6.2. Results of pretreatment experiment II for Dirmstein (ptr-utr = pretreated-untreated).

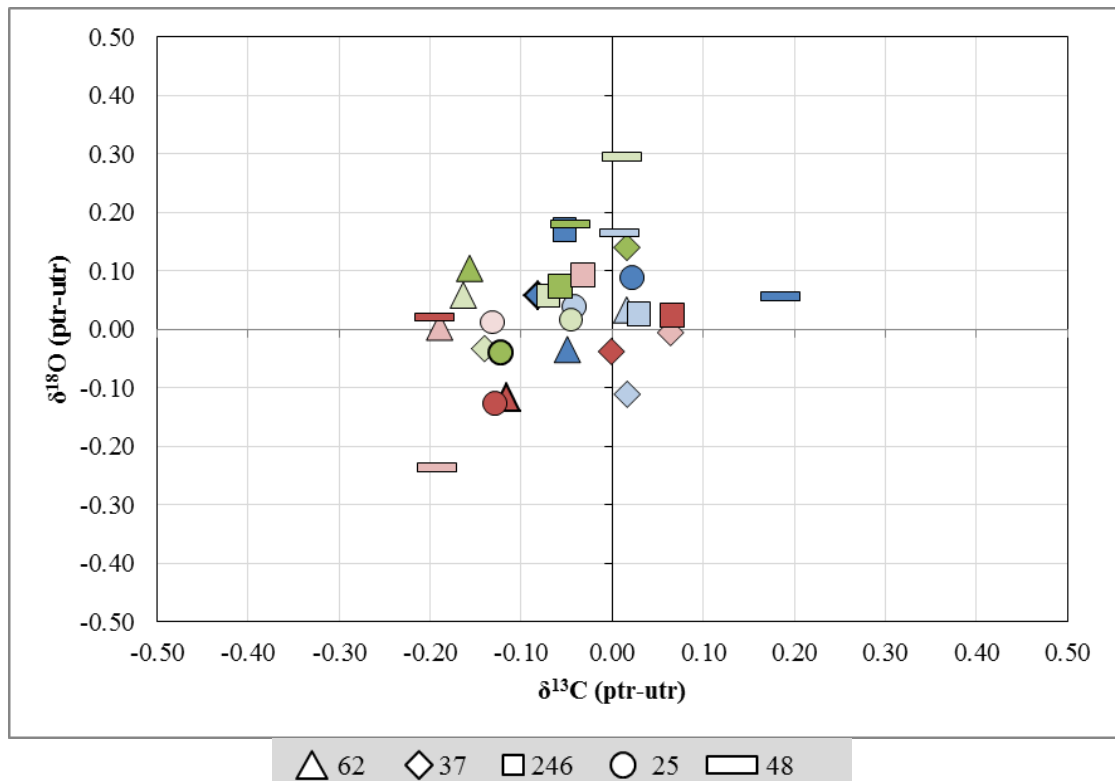


Fig. 6.3. Results of pretreatment experiment II for Eppstein (ptr-utr = pretreated-untreated).

## 6.2 Human data

### 6.2.1 Complete sample set

Oxygen and carbon isotope ratios were determined on the structural carbonate component of bioapatite from 137 human enamel samples. The samples come from 120 individuals from three early medieval cemeteries in the northern Upper Rhine Valley dating to the late 5<sup>th</sup> and early 6<sup>th</sup> century. From 105 individuals one tooth, from 13 two and from two individuals three teeth were measured. Normally each homogenised sample was measured twice and the mean value of both measurements was taken for the evaluation of the data. In several cases sample size was too low or other problems occurred so that only one measurement per sample was possible ( $n = 22$ ). Some samples were measured three times because they were included in the pretreatment experiments. In these cases the mean of three values was used ( $n = 11$ ). The results of all measurements and the accepted mean values for each analysed tooth are listed in Tab. 6.3. Replicate  $\delta^{18}\text{O}$  measurements revealed an average standard deviation of 0.1‰ for  $\delta^{18}\text{O}$  and 0.1‰ for  $\delta^{13}\text{C}$  ( $n = 115$ ). Samples which yielded differences larger than 0.3‰ between the replicates are highlighted in Tab. 6.3. The  $\delta^{18}\text{O}$  of the complete sample set spans from  $-6.8$  to  $-2.3$ ‰ with a mean of  $-4.3 \pm 0.8$ ‰ ( $1\sigma$ ). The  $\delta^{13}\text{C}$  range for all 137 samples is between  $-15.1$  and  $-9.7$ ‰ with a mean of  $-13.3 \pm 0.9$ ‰ ( $1\sigma$ ). The range of values for both  $\delta^{18}\text{O}$  (4.5‰) and  $\delta^{13}\text{C}$  (5.4‰) is large. The  $\delta^{18}\text{O}$  values show nearly a normal distribution but  $\delta^{13}\text{C}$  is not normal distributed (Tab. 10.6; Tab. 10.7; Fig. 10.7).

**Tab. 6.3. Results:  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  for the complete human enamel sample set.**

(Samples which are measured once are marked with an asterisk; samples which yielded differences larger than 0.30‰ between the replicates are in bold)

Site	Grave	Tooth	SD-phase	Sex	Age	$\delta^{13}\text{C}$	$\pm$	$\delta^{18}\text{O}$	$\pm$
Boc	22	M2	5-6	M	Adult	-13.64	0.09	-4.08	0.13
Boc	382	M2	6-7	F	Old adult	-13.44	0.03	-4.79	0.21
Boc	386	P1	6-7	ND	Adult	-13.44	0.05	-3.64	0.05
Boc	391	M2	2-3	F?	Adult	-13.38	0.00	-4.02	0.14
Boc	392	M2	4-7	F	Old adult	-10.38	0.03	-2.80	0.13
Boc	395	M1	5-6	F	Child	-13.14	0.03	-4.22	0.02
Boc	396	M2	4-7	F	Child	-13.69	0.04	-4.77	0.06
Boc	397	P2	4-7	F	Young adult	-13.62	0.03	-4.05	0.19
Boc	398	P2	7-8	M	Old adult	-12.66	0.01	-4.84	0.20
Boc	406	M2	4-5	F	Old adult	-13.21	0.02	-3.44	0.01
Boc	421	P2	6-7	M	Young adult	-14.26	0.02	-3.76	0.10
Boc	423	M1	5-6	ND	Child	-14.03	0.02	-4.07	0.07

Boc	424*	M2	5	F	Adult	-10.43	0.01	-3.92	0.02
Boc	449	M1	3-4	F	Child	-14.08	0.04	-4.19	0.13
Boc	454	P2	5	M?	Adult	-12.76	0.08	-4.56	0.08
Boc	457	M2?	4-5	M?	Young adult	-13.67	0.07	-4.73	0.07
Boc	459	M2	6	M	Adult	-12.33	0.00	-5.73	0.18
Boc	461	M1	4-7	ND	Child	-13.78	0.05	-4.93	0.18
Boc	464	M2	5	?	Young adult	-13.53	0.04	-4.89	0.24
Boc	466	P2?	6	M	Adult	-12.83	0.01	-2.82	0.16
Boc	470	M2	6	F	Young adult	-13.51	0.02	-5.32	0.01
Boc	473	M1	5-7	F	Child	-13.75	0.03	-3.96	0.16
Boc	474	M2	4-7	F	Adult	-12.85	0.08	-4.35	0.17
Boc	478	M2	6-7	F?	Adult	-12.41	0.04	-4.91	0.10
Boc	480	M1	4-7	M?	Child	-14.20	0.00	-3.73	0.01
Boc	482*	M2	3	F	Adult	-11.89	0.01	-2.80	0.01
Boc	486	M2	3-4	F	Adult	-11.81	0.00	-6.82	0.04
Boc	488	M2	3	F	Young adult	-14.18	0.08	-5.36	0.14
Boc	492	P2	6-7	F?	Old adult	-13.27	0.06	-4.32	0.06
Boc	497	P2	4-7	F?	Adult	-12.99	0.00	-5.10	0.02
Dir	4	P2?	5	F	Young adult	-13.60	0.12	-3.53	0.03
Dir	5	M2	5-6	F	Young adult	-13.65	0.02	-2.62	0.09
Dir	5	M3	5-6	F	Young adult	-13.24	0.03	-4.29	0.09
Dir	6	M2	5?	F	Adult	-14.92	0.26	-4.29	0.09
Dir	6	M3	5?	F	Adult	-13.64	0.21	-5.40	0.06
Dir	7	M	5	F	Adult	-13.65	0.10	-2.83	0.03
Dir	24	P2	5	F?	Adult	-13.71	0.03	-4.43	0.06
Dir	24	M2	5	F?	Adult	-13.59	<b>0.32</b>	-4.71	0.21
Dir	24	M3	5	F?	Adult	-12.04	0.15	-4.80	0.07
Dir	25a	P2	nd	M	Old adult	-13.44	0.11	-4.20	0.14
Dir	25a	M3	nd	M	Old adult	-13.29	0.03	-4.89	0.15
Dir	25b*	P2	5?	M	Adult	-12.80	0.01	-5.07	0.03
Dir	25b	M3	5?	M	Adult	-13.01	0.13	-4.70	0.23
Dir	26	M2	5	M	Adult	-13.74	0.01	-4.76	0.01
Dir	26	M3	5	M	Adult	-12.95	0.09	-4.72	0.07
Dir	28*	C	5-6	ND	Adult	-15.09	0.01	-5.66	0.03
Dir	28	P	5-6	ND	Adult	-14.15	0.08	-5.38	0.17
Dir	34	M1	6	F	Child	-13.20	0.22	-4.96	<b>0.37</b>
Dir	35	M2	6 (late)	F	Adult	-12.88	0.05	-4.24	0.00
Dir	35	M3	6 (late)	F	Adult	-13.09	0.02	-5.16	0.01
Dir	42	M1?	6	M	Old adult	-12.91	0.06	-4.21	0.09
Dir	43	M2	6	F	Young adult	-13.80	0.11	-4.34	0.25
Dir	43	M3	6	F	Young adult	-14.03	0.09	-4.82	0.19
Dir	47	M2	5	M	Adult	-13.64	0.15	-4.52	0.15
Dir	4	M3	5	M	Adult	-13.72	0.19	-4.45	0.22
Dir	53	M1	6	F	Child	-14.02	0.04	-3.98	0.21
Dir	55	M1	6	F	Child	-13.63	0.06	-4.89	0.23
Dir	215	M2	6	F	Adult	-13.46	0.03	-4.18	0.24
Dir	236	m1	6	F	Child	-14.54	0.01	-3.22	0.02

## RESULTS

Dir	237	M1	5	M	Child	-14.83	0.09	-4.33	0.03
Dir	238*	M1	5	M	Child	-14.30	0.02	-4.04	0.07
Dir	239*	P2	5	M	Adult	-12.39	0.01	-4.81	0.02
Dir	239	M2	5	M	Adult	-12.88	0.02	-5.36	0.12
Dir	239	M3	5	M	Adult	-13.27	0.13	-4.37	0.12
Dir	244*	M2	5	M	Old adult	-13.19	0.01	-5.84	0.03
Dir	244	M3	5	M	Old adult	-14.13	0.16	-5.80	0.20
Dir	254	M2	6	F	Young adult	-13.90	0.04	-3.72	0.16
Dir	254	M3	6	F	Young adult	-13.65	0.03	-4.08	0.17
Dir	255*	M1	5	M	Old adult	-14.34	0.01	-5.51	0.03
Dir	255*	M3	5	M	Old adult	-13.25	0.02	-4.99	0.02
Dir	256	M2	6	M	Adult	-13.64	0.14	-4.82	<b>0.51</b>
Dir	256	M3	6	M	Adult	-13.52	0.09	-5.13	0.05
Epp	3	M2	6-7	M	Adult	-13.43	0.00	-4.10	0.11
Epp	4C*	M2	6-7	F	Young adult	-13.48	0.09	-4.84	0.07
Epp	25	M2	6?	M	Child	-13.80	0.04	-4.90	0.04
Epp	29	M	6	F	Adult	-12.92	0.01	-4.22	0.04
Epp	30	P	6	F	Old adult	-13.81	0.29	-4.26	0.01
Epp	35	M2	4	M	Adult	-13.47	0.05	-4.31	0.06
Epp	37	M2	4-5?	M	Young adult	-13.93	0.06	-4.05	0.09
Epp	38	M2	5	M	Adult	-14.31	0.01	-3.53	0.04
Epp	39	M2	6?	F	Old adult	-12.61	0.05	-4.08	0.09
Epp	46*	M2	5	M	Young adult	-13.90	0.01	-3.72	0.01
Epp	47	M2	4-5?	M?	Adult	-13.11	0.00	-5.07	0.08
Epp	48*	M2	4	M	Young adult	-12.70	0.01	-2.31	0.01
Epp	49	M2	4?	M?	Adult	-13.33	0.01	-4.96	0.19
Epp	50*	M3?	2-3	ND	Adult	-9.74	0.01	-5.58	0.01
Epp	52	M1?)	2	M?	Adult	-14.87	0.07	-4.93	0.01
Epp	55	P2	6	F	Adult	-12.90	0.23	-4.48	<b>0.72</b>
Epp	58	P2	4-5?	?	Adult	-11.66	0.05	-4.06	0.07
Epp	61	M2	6	F?	Adult	-12.37	0.01	-4.82	0.15
Epp	62*	M2	5-6	M	Young adult	-13.30	0.01	-4.26	0.02
Epp	66	M2?	2-3?	ND	Young adult	-13.71	0.14	-2.72	0.14
Epp	67A	C?	5?	F	Old adult	-13.21	0.03	-4.19	0.05
Epp	67C	M2?	2	F	Young adult	-13.32	0.02	-5.59	0.08
Epp	70	M1?	6	F	Old adult	-12.68	0.06	-3.97	0.15
Epp	71	M2	6/7?	M	Old adult	-13.47	0.02	-4.27	0.01
Epp	74	M2	6-7	M	Adult	-13.45	0.27	-4.45	0.05
Epp	83	M2	3	F	Young adult	-11.19	0.03	-5.34	0.07
Epp	111	M2	5	M	Young adult	-13.11	0.01	-5.19	0.01
Epp	162	M2	6	M	Young adult	-14.23	0.03	-4.14	0.01
Epp	167	P2	6	?	Young adult	-13.14	<b>0.33</b>	-4.07	0.02
Epp	168	M1	6	M	Child	-13.14	0.41	-3.33	0.12
Epp	182	M1	6	M	Child	-13.93	0.05	-2.61	0.06
Epp	188	M2	6?	F	Adult	-13.97	0.02	-4.87	0.00
Epp	189	M1	5	?	Child	-14.47	0.03	-4.07	0.01
Epp	192	M1	5	F?	Child	-14.30	0.09	-2.99	0.03

Epp	197	M2?	6	F	Young adult	-12.92	0.29	-3.68	0.06
Epp	198	M2	6	F	Young adult	-11.18	0.05	-3.17	0.01
Epp	208	M2	5-6	ND	Adult	-13.94	0.02	-4.81	0.20
Epp	211	P1	5(-6)	?	Adult	-14.24	<b>0.59</b>	-4.47	0.29
Epp	217	M1?	6	F	Child	-14.26	0.16	-3.63	0.18
Epp	222	P1	5	M	Adult	-12.77	<b>0.38</b>	-4.16	<b>0.52</b>
Epp	224	m1	6	M	Child	-12.67	0.07	-3.23	0.24
Epp	226	M2	6	F	Adult	-13.32	0.01	-4.87	0.10
Epp	228	M2	6	F	Young adult	-13.63	0.08	-3.85	0.07
Epp	233*	P2	6-7	M	Adult	-12.51	0.01	-4.41	0.01
Epp	245	M1	6-7	ND	Child	-12.84	<b>0.65</b>	-3.27	<b>0.33</b>
Epp	246	M2	6	M	Adult	-13.54	0.07	-3.57	0.15
Epp	275	M3?	2	ND	Adult	-14.33	0.00	-4.30	0.07
Epp	279	M	6	M	Adult	-13.79	0.05	-3.54	0.22
Epp	280	P2	2?	F?	Adult	-12.80	0.02	-4.47	0.02
Epp	391	P?	6	M	Adult	-11.07	<b>0.97</b>	-4.32	0.05
Epp	396	M2	2	M	Young adult	-13.60	0.10	-5.14	0.00
Epp	405	M2	6	M	Old adult	-13.72	<b>0.45</b>	-4.16	<b>0.31</b>
Epp	411	M1	5	F	Child	-13.06*	0.01	-3.84*	0.02
Epp	413	M2	5?	F	Young adult	-14.02	0.02	-5.47	0.00
Epp	418	M2?	5	F?	Adult	-13.35*	0.01	-5.07*	0.01
Epp	421	P?	6	F	Adult	-12.65	<b>1.44</b>	-4.04	0.16
Epp	422	M1	6	M	Child	-13.88	0.04	-3.90	0.25
Epp	425	M2	4?	M	Young adult	-11.88*	0.01	-3.60*	0.02
Epp	426B	P2	5?	M	Young adult	-12.50	0.01	-4.46	0.13
Epp	428	m1?	3-5?	ND	Child	-12.91*	0.01	-3.00*	0.04
Epp	431	P1	4?	F	Adult	-10.92*	0.02	-4.26*	0.07
Epp	433	M2	4	F	Young adult	-13.31	0.02	-3.77	0.18
Epp	435	M1	6	F	Child	-13.31	0.06	-4.10	0.08
Epp	436	M2	4-5	M	Old adult	-12.47	0.04	-5.44	0.07
Epp	437	M2	4?	M	Young adult	-14.06	0.01	-3.67	0.03

### 6.2.1.1 Sources of variation within the data set

Samples thought to represent local resident communities are expected to have  $\delta^{18}\text{O}$  ranges between 1–2 ‰ (e.g. White et al. 2001, 66, with citations therein) but can vary according to environment, seasonal variation, dietary and cultural habits. A source of variation in  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  may derive from differences in the types of teeth analysed. The majority of the samples is comprised of teeth which mineralise after or partially after weaning (P1, P2, M2, M3) but in several cases teeth were analysed which develop prior to weaning (m1, M1, C). As breast milk is enriched in  $\delta^{18}\text{O}$  relative to drinking water, teeth that developed before weaning are expected to have higher  $\delta^{18}\text{O}$  values compared to later-forming teeth (Roberts et al. 1988, Wright/Schwarz 1998).

Additionally,  $\delta^{13}\text{C}$  may decrease with age as a result of the declining importance of isotopically light lipids from breast milk given that there is no large difference between the solid diets of children and their mothers (Wright/Schwarcz 1998, Dupras et al. 2001). A scatter plot of  $\delta^{18}\text{O}$  against  $\delta^{13}\text{C}$  values for different tooth types shows that first permanent molars have elevated  $\delta^{18}\text{O}$  and decreased  $\delta^{13}\text{C}$  values in comparison to later forming teeth (Fig. 6.4). The same picture is visible when comparing  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  box plots for the different tooth types (Fig. 6.5). The differences of mean  $\delta^{18}\text{O}$  values are statistically significant for M1 and P2, as well as for M1 and M3. The differences are also significant between M1 and M2 when outlying  $\delta^{18}\text{O}$  were removed from the M2 data set (Tab. 6.4). For mean  $\delta^{13}\text{C}$  values all differences between the M1 and the other teeth are statistically significant (Tab. 6.4).

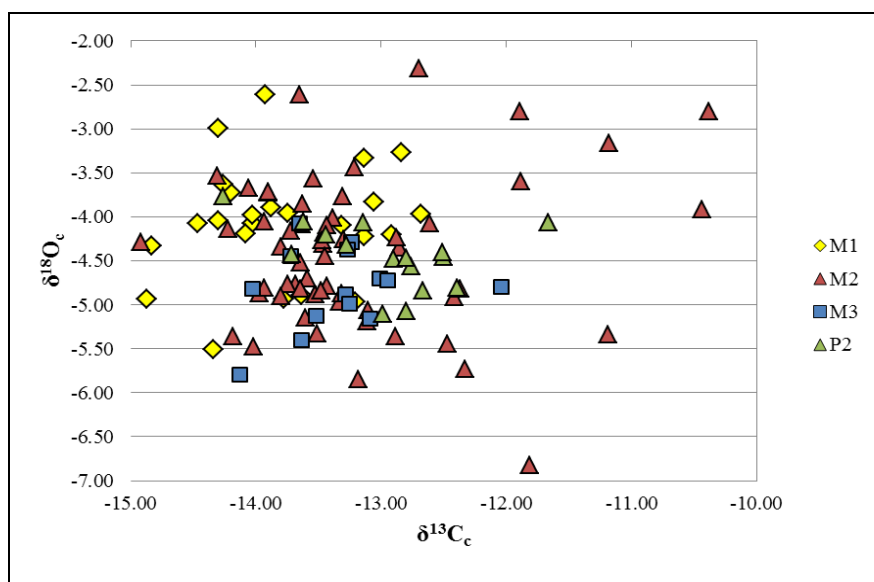


Fig. 6.4. Scatter plot  $\delta^{18}\text{O}$  against  $\delta^{13}\text{C}$  for different tooth types.

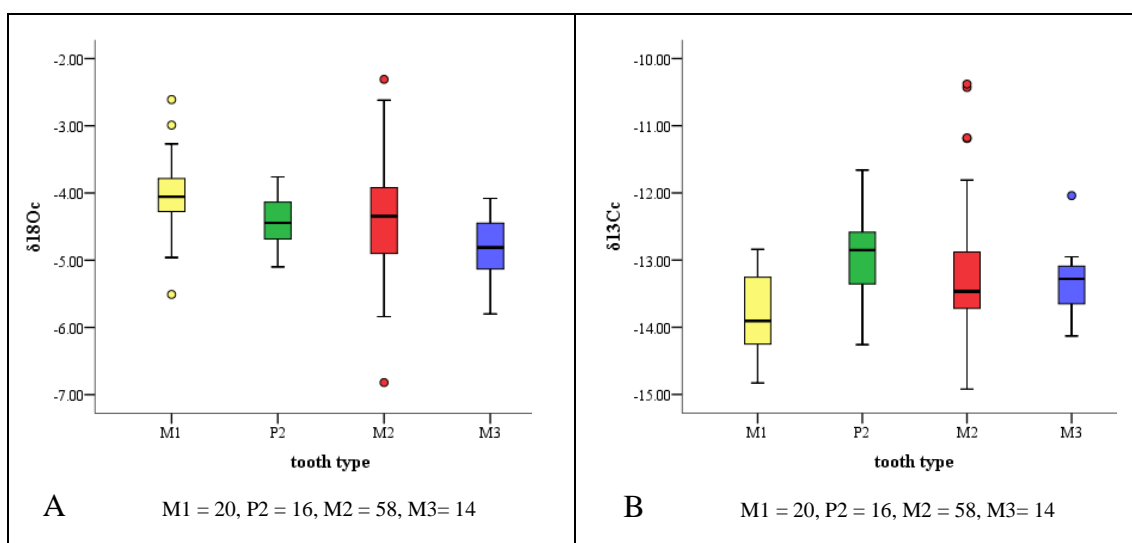


Fig. 6.5. Box plots  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  different tooth types.

**Tab. 6.4. Differences between tooth types for  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ .**

$\delta^{18}\text{O}$	M1/P2	M1/M2	M1/M3	P2/M2	P2/M3	M2/M3
<b>Mann-Whitney U</b>	89.000	415.500	44.500	460.000	60.000	275.500
<b>Wilcoxon W</b>	225.000	2,126.500	149.500	596.000	165.000	380.500
<b>Z</b>	-2.261	-1.883	-3.342	-.053	-2.162	-1.857
<b>Asymp. Sig. (2-tailed)</b>	<b>.024</b>	.060 (.010)*	<b>.001</b>	.958	<b>.031</b>	.063
<b>Exact Sig. [2*(1-tailed Sig.)]</b>	.023		.000		.031	
$\delta^{13}\text{C}$	M1/P2	M1/M2	M1/M3	P2/M2	P2/M3	M2/M3
<b>Mann-Whitney U</b>	44.000	333.000	77.500	318.500	65.500	399.500
<b>Wilcoxon W</b>	254.000	543.000	287.500	2,029.500	167.500	2,110.500
<b>Z</b>	-3.694	-2.827	-2.188	-1.911	-2.058	-.092
<b>Asymp. Sig. (2-tailed)</b>	<b>.000</b>	<b>.0005</b>	<b>.029</b>	.056	<b>.040</b>	.926
<b>Exact Sig. [2*(1-tailed Sig.)]</b>	.000		.027		.038	

\*Excluding outlying  $\delta^{18}\text{O}$  for M2

An additional source of variation may be temporal differences in  $\delta^{18}\text{O}$  values as a result of climatic shifts. The complete sample set spans a range of around 150 years and can be divided in five periods (SD-phases 2 to 6) each representing roughly a generation of 20 to 30 years. Unfortunately it was not possible to assign every grave to a certain period with safety. The sample size for the early periods (SD-phases 2-4) is therefore relatively low. Additionally, the sample size is reduced as primary first molars as well as individuals with non-local  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures have to be excluded. In order to increase the sample size the samples of the SD-phases 2-4 were summarised ( $n = 5$ ). The difference of the mean  $\delta^{18}\text{O}$  values between the remaining three groups is low (SD-phases 2–4 =  $-4.0 \pm 1.1\text{‰}$  ( $n = 5$ ), SD-phase 5 =  $-4.4 \pm 0.5\text{‰}$  ( $n = 17$ ), SD-phase 6 =  $-4.3 \pm 0.7\text{‰}$  ( $n = 15$ ) and statistically not significant.

#### 6.2.1.2 Determination of the local oxygen range

For the determination of the local  $\delta^{18}\text{O}$  range in the northern Upper Rhine Valley during the late 5<sup>th</sup> and 6<sup>th</sup> centuries, all P, M2 and M3 of individuals with a local  $^{87}\text{Sr}/^{86}\text{Sr}$  signature (within 0.70900–0.71000) were used. The 62 enamel samples exhibit a mean of  $-4.3 \pm 0.7\text{‰}$ . The values show a normal distribution with three extreme values higher than  $-3.0\text{‰}$ . When these outliers were excluded, the  $\delta^{18}\text{O}_c$  values range from  $-5.7$  to  $-3.2\text{‰}$  with a mean of  $-4.4 \pm 0.5\text{‰}$  ( $n = 59$ ). When considering a variation of 1–2‰ between individuals of a community using the same drinking water source, the local range is most probably between  $-5.4$  to  $-3.4\text{‰}$ .

### 6.2.2 Eppstein

From the cemetery Eppstein  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values of 65 human enamel samples were determined. The  $\delta^{18}\text{O}$  values exhibit a range from  $-5.6$  to  $-2.3\text{‰}$  with a mean of  $-4.2 \pm 0.7\text{‰}$ . The distribution is approximately normal (Shapiro Wilk  $p = 0.509$ ) although there is a skewness towards isotopically heavier values (Fig. 10.10). The mean  $\delta^{18}\text{O}$  of early forming teeth (M1/M1?/C?) is  $-3.7 \pm 0.6\text{‰}$  ( $n = 12$ ). Later forming teeth have mean  $\delta^{18}\text{O}$  of  $-4.3 \pm 0.2\text{‰}$  (P1/P2/P/P? = 12) and  $-4.3 \pm 0.8\text{‰}$  (M2/M2? = 35) (Fig. 6.6A, B). The difference between early and later forming teeth is statistically significant (Mann-Whitney U test,  $p = 0.006$ ). This trend is also visible when only individuals with local strontium signatures were used or only teeth that can be determined with safety. There are no significant differences between the mean  $\delta^{18}\text{O}$  values of adult female individuals (mean  $-4.5 \pm 0.7\text{‰}$ ,  $n = 18$ ) and adult male individuals (mean  $-4.2 \pm 0.7\text{‰}$ ,  $n = 23$ ) (calculated without early forming teeth) (Fig. 6.6D, E). The significant difference in mean  $\delta^{18}\text{O}$  values between children and the older age groups (child:  $-3.6 \pm 0.6\text{‰}$ ,  $n = 12$ ; young adult:  $-4.2 \pm 0.9\text{‰}$ ,  $n = 20$ ; adult:  $-4.5 \pm 0.5\text{‰}$ ,  $n = 26$ , old adult:  $-4.3 \pm 0.5\text{‰}$ ,  $n = 7$ , Mann-Whitney U test,  $p = 0.001$ ) is the result of the sampling of mainly M1 from non-adult individuals. The mean  $\delta^{18}\text{O}$  values for the earliest period (SD-phase 2–3: mean =  $-4.7 \pm 1.0\text{‰}$ ,  $n = 7$ ) are lower than for the following periods (SD-phase 4, 4?: mean =  $-3.8 \pm 0.8\text{‰}$ ,  $n = 7$ ; SD-phase 5, 5?: mean =  $-4.5 \pm 0.8\text{‰}$ ,  $n = 7$ ; SD-phase 6, 6?: mean =  $-4.2 \pm 0.5\text{‰}$ ,  $n = 16$ ) (Fig. 6.7). The difference is only significant between the earliest period and the SD-phase 4 (Mann-Whitney U test,  $p = 0.048$ ) but the samples size is relatively low. Early forming teeth as well as values from graves that cannot be assigned to a specific period (SD-phases 4–5, 5–6, 6–7) were excluded from this calculation.

The  $\delta^{13}\text{C}$  show a large variability ranging from  $-14.9$  to  $-9.7\text{‰}$  with a mean of  $-13.2 \pm 0.9\text{‰}$ . The data is not normally distributed and is skewed toward isotopically heavier values (Shapiro-Wilk test,  $p = 0.000$ ) (Fig. 10.10). The mean  $\delta^{13}\text{C}$  of early forming teeth is  $-13.7 \pm 0.7\text{‰}$  (M1/M1?/C? = 12). Later forming teeth have mean  $\delta^{13}\text{C}$  values of  $-12.6 \pm 1.0\text{‰}$  (P1/P2/P/P? = 12) and  $-13.3 \pm 0.8\text{‰}$  (M2/ M2? = 35) (Fig. 6.6A, C). The differences are significant between M1/M1?/C? and P1, P2, P, P? (Mann-Whitney U test,  $p = 0.004$ ) but not between M1/M1?/C? and M2/M2? (Mann-Whitney U test,  $p = 0.438$ ). This trend is also visible when only individuals with local strontium signatures or only teeth that can be determined with safety, or both, were



used. There are also no significant differences in mean  $\delta^{13}\text{C}$  values between adult female individuals (mean  $-12.9 \pm 0.9\text{‰}$ ,  $n = 18$ ) and adult male individuals (mean  $-13.2 \pm 0.8\text{‰}$ ,  $n = 23$ ) (calculated without early forming teeth) as well as between age groups (child:  $-13.6 \pm 0.6\text{‰}$ ,  $n = 12$ ; young adult:  $-13.2 \pm 0.9\text{‰}$ ,  $n = 20$ ; adult:  $-13.0 \pm 1.2\text{‰}$ ,  $n = 26$ , old adult:  $-13.1 \pm 0.6\text{‰}$ ,  $n = 7$ ) and time periods (SD-phases 2, 2–3, 3: mean =  $-12.7 \pm 1.6\text{‰}$ ,  $n = 7$ ; SD-phase 4, 4?: mean =  $-12.8 \pm 1.1\text{‰}$ ,  $n = 7$ ; SD-phase 5, 5?: mean =  $-13.4 \pm 0.7\text{‰}$ ,  $n = 7$ ; SD-phase 6, 6?: mean =  $-13.1 \pm 0.9\text{‰}$ ,  $n = 16$ ). Early forming teeth as well as values from graves that cannot be assigned to a specific period (SD-phases 4–5, 5–6, 6–7) were excluded from this calculation. However, the earliest periods (SD-phases 2, 2–3, 4, 4–5) have the largest dispersion and slightly elevated  $\delta^{13}\text{C}$  values in comparison to later periods.

When excluding all early forming teeth and only including individuals with a local strontium signature, the trimmed sample set ( $n = 23$ ) with a mean of  $-4.2\text{‰} \pm 0.7\text{‰}$  ranges from  $-5.4\text{‰}$  to  $-2.3\text{‰}$ . The  $\delta^{18}\text{O}$  value of  $-2.3\text{‰}$  is an outlier and was only measured once, therefore, it might also be an erroneous value and should be excluded. The remaining data set ( $n = 22$ ) is normally distributed (Shapiro Wilk  $p = 0.871$ ) and ranges from  $-5.4\text{‰}$  to  $-3.2\text{‰}$  with a mean of  $-4.3\text{‰} \pm 0.6\text{‰}$ . This is in good accordance with the local  $\delta^{18}\text{O}$  range which was determined from the complete data set for the Upper Rhine Valley (mean  $-4.4\text{‰} \pm 0.5\text{‰}$ ,  $n = 53$ ).

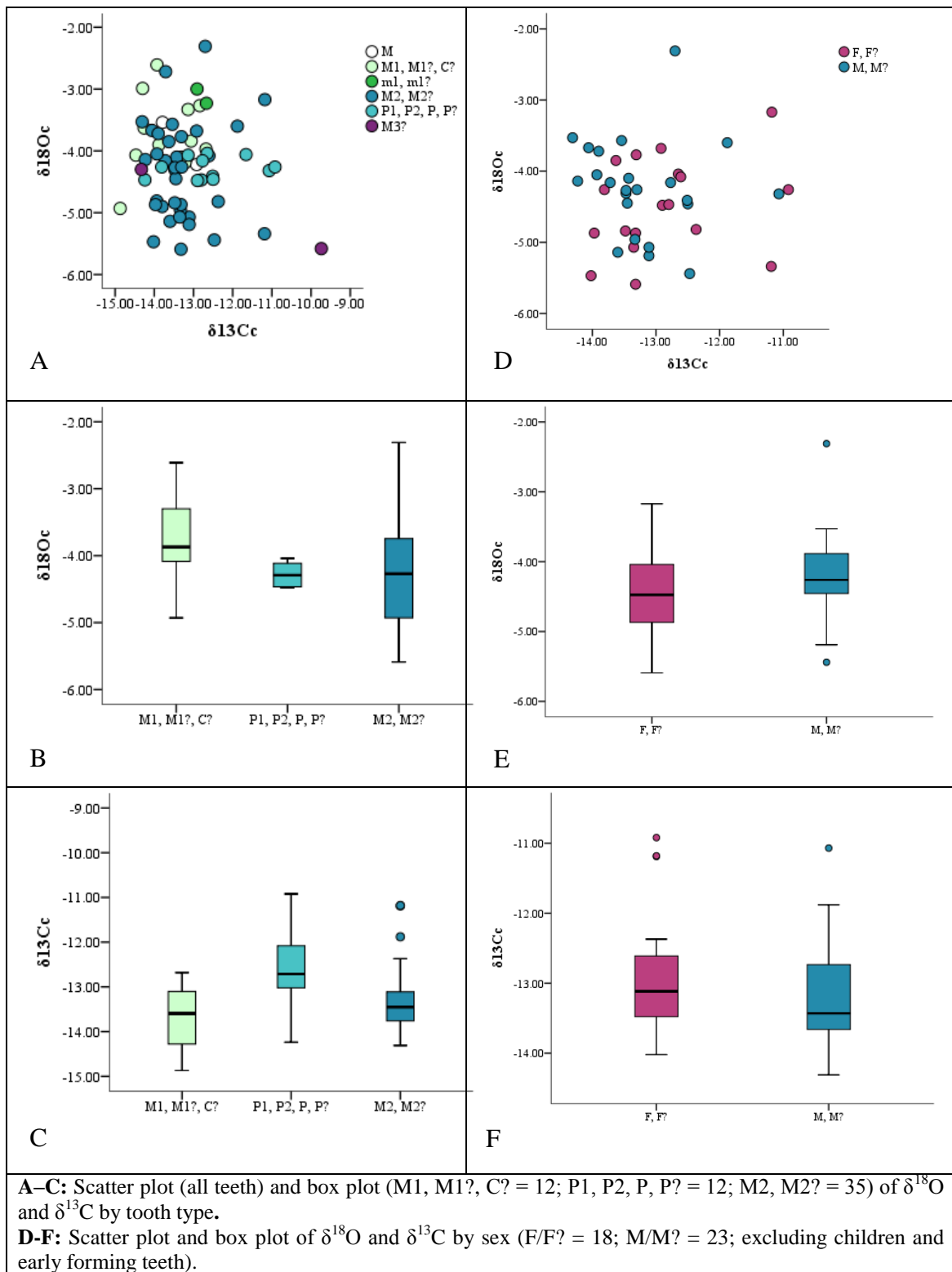
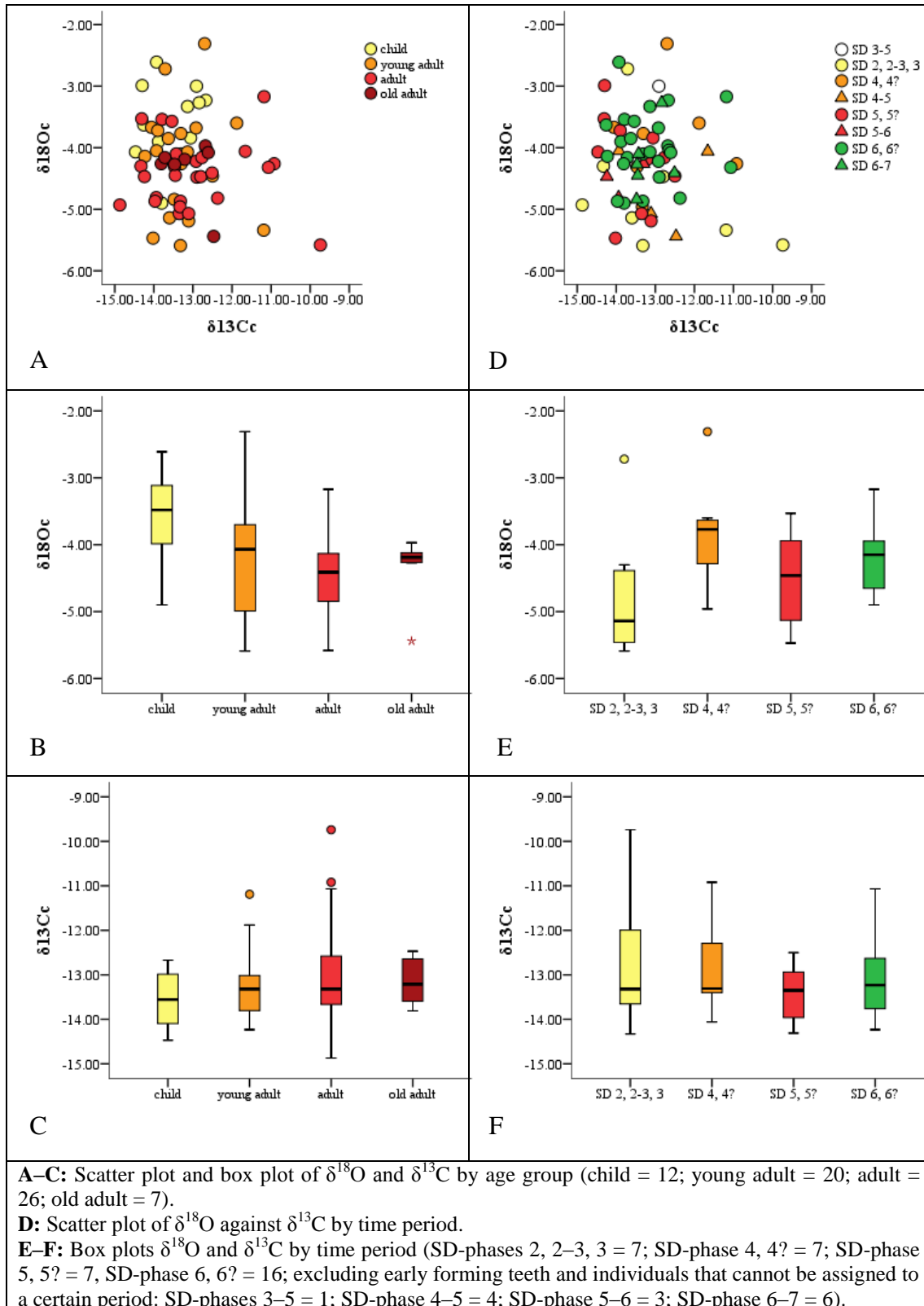


Fig. 6.6. Eppstein  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  results by tooth type and sex.



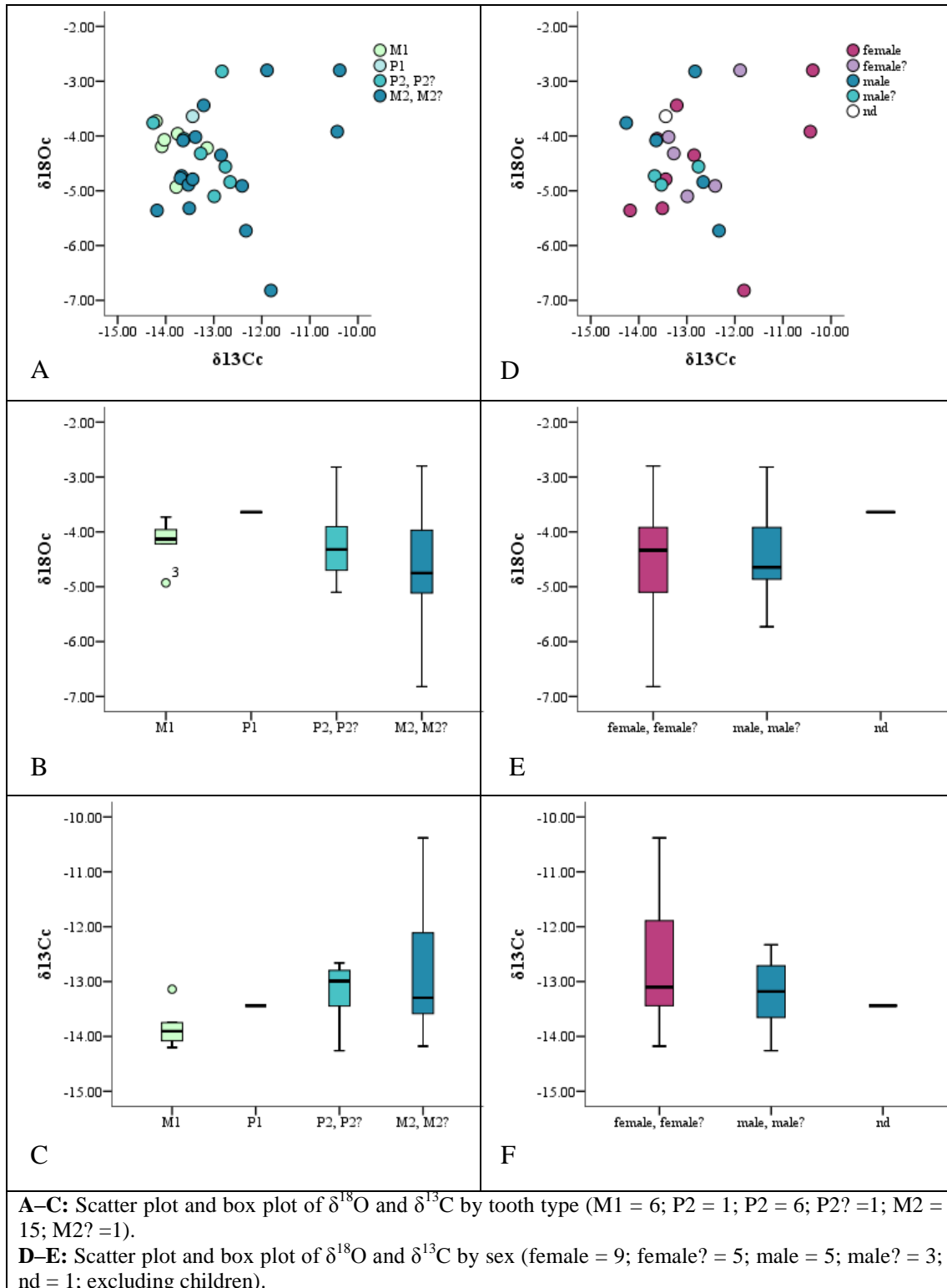
**Fig. 6.7.** Eppstein  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  results by age group and period.

### 6.2.3 Bockenheim

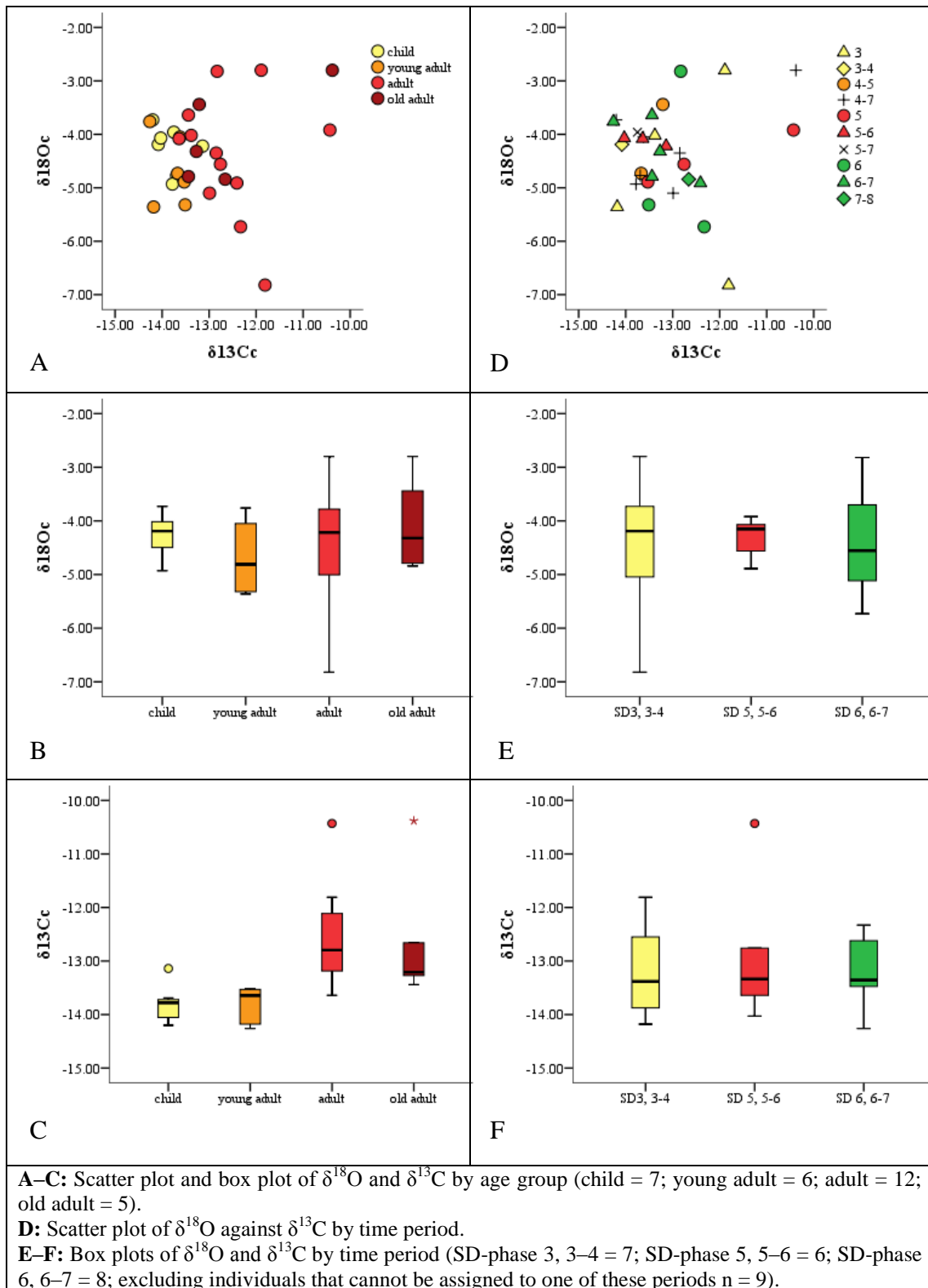
Oxygen and carbon isotopes of the structural carbonate from 30 tooth enamel samples originating from 30 individuals from the cemetery Bockenheim were determined. The results and relevant information are summarised in Tab. 6.3. The  $\delta^{18}\text{O}$  values of the complete data set range from  $-6.8$  to  $-2.8\text{‰}$  with a mean of  $-4.4 \pm 0.9\text{‰}$  ( $1\sigma$ ). The data is normally distributed (Shapiro-Wilk test,  $p = 0.357$ ) with some extreme values at each end (Fig. 10.8). The mean  $\delta^{18}\text{O}$  of permanent first molars ( $n = 6$ ) is  $-4.2 \pm 0.4\text{‰}$  and slightly elevated in comparison to that of later forming teeth (M2/P1/P2,  $n = 24$ )  $-4.4 \pm 1.0\text{‰}$  but the difference is not significant (Mann-Whitney U test,  $p = 0.534$ ) (Fig. 6.8A, B). Adult female individuals have a mean of  $-4.4 \pm 1.1\text{‰}$  ( $n = 14$ ); almost the same mean  $\delta^{18}\text{O}$  value as adult male individuals with  $-4.4 \pm 0.87\text{‰}$  ( $n = 8$ ) (Fig. 6.8D, E) There are also no significant differences in mean  $\delta^{18}\text{O}$  values between age groups or time periods (Fig. 6.9A, B; Fig. 6.9D, E). However, the earliest graves show the largest variation in  $\delta^{18}\text{O}$  values in comparison to the other periods (Fig. 6.9A, E).

The  $\delta^{13}\text{C}$  data of the 30 samples have a range between  $-14.3$  and  $-10.4\text{‰}$  with a mean of  $-13.1 \pm 1.0\text{‰}$  ( $1\sigma$ ). The data is not normally distributed and has two extreme values (Shapiro-Wilk test,  $p = 0.001$ ; Fig. 10.8). The mean  $\delta^{13}\text{C}$  of the first permanent molars ( $n = 6$ ) is  $-13.8 \pm 0.9\text{‰}$ , and decreased in comparison to later forming teeth (M2/P1/P2,  $n = 24$ ) which have a mean value of  $-12.9 \pm 1.0\text{‰}$ . This difference is statistically significant (Mann-Whitney U,  $p = 0.010$ ) (Fig. 6.8A, C). Adult female individuals have a mean of  $-12.7 \pm 1.2\text{‰}$  ( $n = 14$ ); a slightly higher mean  $\delta^{13}\text{C}$  value than adult male individuals with  $-13.2 \pm 0.7\text{‰}$  ( $n = 8$ ) (Fig. 6.8D, F) but the difference is not significant (Mann-Whitney U,  $p = 0.306$ ). There are significant differences in mean  $\delta^{13}\text{C}$  values between the two younger age groups (child: mean =  $-13.8 \pm 0.4\text{‰}$ ,  $n = 7$ ; young adult: mean =  $-13.8 \pm 0.3\text{‰}$ ,  $n = 6$ ) and the older age groups (adult: mean =  $-12.6 \pm 0.9\text{‰}$ ,  $n = 12$ ; old adult: mean =  $-12.6 \pm 1.3\text{‰}$ ,  $n = 5$ ) (Mann-Whitney U,  $p = 0.000$ ) (Fig. 6.9A, C). While the difference of the group of children can be explained by the fact that only M1 were analysed, the difference of the young adult from the older groups is striking as only later forming teeth were analysed. There are no differences in mean  $\delta^{13}\text{C}$  values between the different time periods Fig. 6.9D, F). When excluding early forming teeth and individuals with a non-local strontium signature, the sample set ( $n = 18$ ) shows a

normal distribution (Shapiro-Wilk test,  $p = 0.996$ ) with a mean of  $-4.4 \pm 0.2\text{‰}$  and a range from  $-5.7$  to  $-2.8\text{‰}$ . This is in good accordance with the local  $\delta^{18}\text{O}$  range which was determined from the complete data set (mean  $-4.4\text{‰} \pm 0.5\text{‰}$  ( $n = 53$ )).



**Fig. 6.8. Bockenheim  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  by tooth type and sex.**



**Fig. 6.9. Bockenheim  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  by age group and period.**

#### 6.2.4 Dirmstein

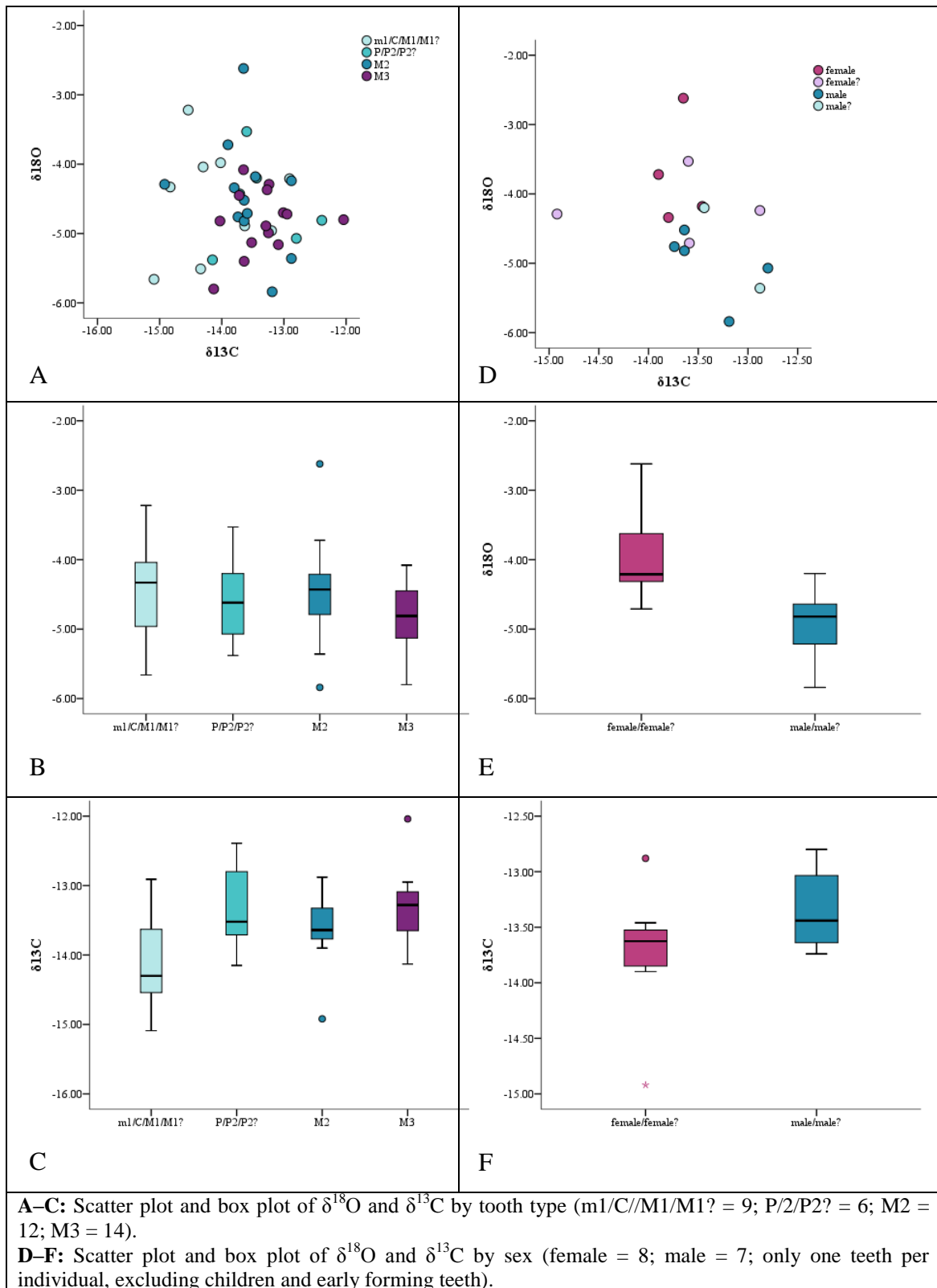
Results of the  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values of 42 tooth enamel samples from 25 individuals from the cemetery Dirmstein are summarised in Tab. 6.3 and presented in Fig. 6.10 and 6.11. In ten cases only one, in 13 cases two, and in two cases three teeth per individual were analysed. The  $\delta^{18}\text{O}$  values of the complete sample set have a large variability, ranging from  $-5.8$  to  $-2.6\text{‰}$  with a mean of  $-4.6 \pm 0.7\text{‰}$  ( $1\sigma$ ). The sample set shows a normal distribution (Shapiro-Wilk test  $p = 0.164$ ) with a skewness toward heavier values (Fig. 10.9). Early forming teeth are not significantly enriched in mean  $\delta^{18}\text{O}$  values in comparison to later forming teeth (m/C/M1/M1?: mean =  $-4.5 \pm 0.8\text{‰}$ ,  $n = 9$ ; P/P2/P2?: mean =  $-4.6 \pm 0.66\text{‰}$ ,  $n = 6$ ; M2: mean =  $-4.5 \pm 0.8\text{‰}$ ,  $n = 12$ ; M3: mean =  $-4.8 \pm 0.5\text{‰}$ ,  $n = 14$ ). This is also the case when individuals with non-local strontium values were excluded. However, Fig. 6.10A and B show clearly the tendency for earlier forming teeth to have elevated  $\delta^{18}\text{O}$  values. There are significant differences between male and female individuals when M2 and P2 (female: mean =  $-4.0 \pm 0.7\text{‰}$ ,  $n = 8$ ; male: mean =  $-4.9 \pm 0.5\text{‰}$ ,  $n = 7$ ) were compared (Mann Whitney U test sig. = 0.008). The tendency is for women to have increased  $\delta^{18}\text{O}$  values in comparison to men. The mean  $\delta^{18}\text{O}$  for M3 of female individuals (mean =  $-4.8 \pm 0.5\text{‰}$ ,  $n = 6$ ) is also slightly higher than that of male individuals (mean =  $-4.9 \pm 0.5\text{‰}$ ,  $n = 8$ ) but the difference is not significant. When only M2/P2 were compared, the  $\delta^{18}\text{O}$  values of young adults (mean =  $-3.6 \pm 0.7\text{‰}$ ,  $n = 4$ ) is increased in comparisons to children (mean =  $-4.2 \pm 0.7\text{‰}$ ,  $n = 6$ ), adults (mean =  $-4.6 \pm 0.7\text{‰}$ ,  $n = 11$ ) and older adults (mean =  $-4.9 \pm 0.9\text{‰}$ ,  $n = 4$ ), but the samples size is low. This is also the case for the M3; younger adults have a mean  $\delta^{18}\text{O}$  value of  $-4. \pm 0.4$  ( $n = 3$ ), whereas adult individuals (mean =  $-4.8 \pm 0.4\text{‰}$ ,  $n = 8$ ) and older adults (mean =  $-5.2 \pm 0.5\text{‰}$ ,  $n = 3$ ) have slightly decreased values but the differences are not significant. There is no difference in mean  $\delta^{18}\text{O}$  values between the SD-phases 5 (mean =  $-4.5 \pm 0.9\text{‰}$ ,  $n = 10$ ) and 6 (mean =  $-4.3 \pm 0.5\text{‰}$ ,  $n = 10$ ).

The  $\delta^{13}\text{C}$  data of the 42 samples have a range between  $-15.1\text{‰}$  and  $-12.0\text{‰}$  with a mean of  $-13.6\text{‰} \pm 0.6\text{‰}$  ( $1\sigma$ ). The data is normally distributed (Shapiro-Wilk  $p = 0.511$ ) and has two extreme values (Fig. 10.9). The mean  $\delta^{13}\text{C}$  of early forming teeth (m1/C/M1:  $n = 9$ ) is  $-14.1\text{‰} \pm 0.7\text{‰}$ , and decreased in comparison to later forming teeth (P/P2: mean =  $-13.4 \pm 0.7\text{‰}$ ,  $n = 6$ ; M2: mean =  $-13.6 \pm 0.5\text{‰}$ ,  $n = 12$ ; M3: mean =  $-13.6 \pm 0.5\text{‰}$ ,  $n = 14$ ) but the difference is only significant between

early forming teeth and M3 (Mann-Whitney U,  $p = 0.038$ ). There are no significant differences between female and male individuals when M2 and P2 (female: mean =  $-13.7 \pm 0.6\text{‰}$ ,  $n = 8$ ; male: mean =  $-13.3 \pm 0.4\text{‰}$ ,  $n = 7$ ) were compared. The mean  $\delta^{13}\text{C}$  for M3 of female individuals (mean =  $-13.3 \pm 0.7\text{‰}$ ,  $n = 6$ ) is very similar to that of male individuals (mean =  $-13.4 \pm 0.4\text{‰}$ ,  $n = 8$ ). The  $\delta^{13}\text{C}$  values between age groups are very similar (children: mean =  $-14.1 \pm 0.6\text{‰}$ ,  $n = 6$ ; young adults: mean =  $-13.7 \pm 0.1\text{‰}$ ,  $n = 4$ ; adults: mean =  $-13.7 \pm 0.8\text{‰}$ ,  $n = 11$ ; older adults: mean =  $-13.5 \pm 0.6\text{‰}$ ,  $n = 4$ ); only the  $\delta^{13}\text{C}$  values of children are slightly decreased. The  $\delta^{13}\text{C}$  values of M3 between age groups are also very similar (younger adults: mean =  $-13.6 \pm 0.4\text{‰}$ ,  $n = 3$ ; adults: mean =  $-13.2 \pm 0.5\text{‰}$ ,  $n = 8$ ; older adults: mean =  $-13.6 \pm 0.5\text{‰}$ ,  $n = 3$ ). There is no difference in mean  $\delta^{13}\text{C}$  values between the SD-phases 5 (mean =  $-13.8 \pm 0.6\text{‰}$ ,  $n = 10$ ) and 6 (mean =  $-13.6 \pm 0.5\text{‰}$ ,  $n = 10$ ).

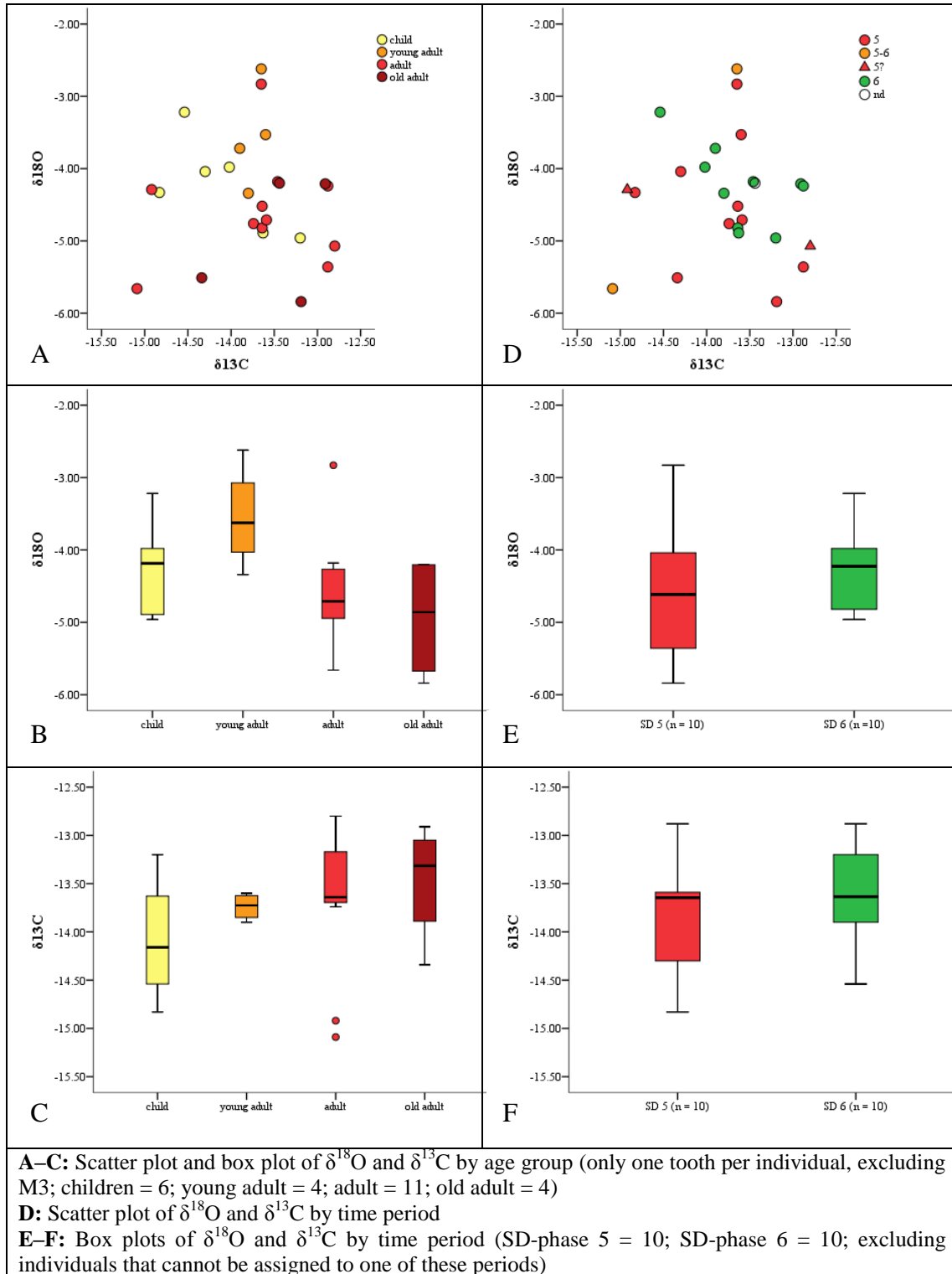
By removing individuals with non-local strontium values over 0.71050 and early forming teeth which can be influenced by a breastfeeding signal the values show a range between  $-5.4\text{‰}$  and  $-2.6\text{‰}$  with a mean of  $-4.5\text{‰}$  ( $\pm 0.6\text{‰}$ ,  $1\sigma$ ,  $n = 21$ ). Considering  $1\text{‰}$  total variation or the normal standard deviation, a range between at least  $-3.9\text{‰}$  and  $-5.0\text{‰}$  has to be seen as the local oxygen value.





**Fig. 6.10.** Dirmstein  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  by tooth type and sex.

RESULTS



**Fig. 6.11. Dirmstein  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  by age group and period.**

### 6.3 Sequential cattle samples

A total of eight teeth from four cattle were analysed for  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ . One cattle was from Dirmstein (Dir263) and three from Bockenheim (Boc195/181, Boc274; Boc532). From each animal two teeth, the M2 and M3, were analysed. The enamel from the M2 reflects the conditions during the first year of life while the M3 is formed during the second year of life of the animal (Knipper 2011, 134–135; 134, Fig. 8.4). Based on the sequential sampling technique between 8 and 14 samples per tooth were obtained in equally spaced horizontal lines. Results are reported in Tab. 10.8 and presented in Fig. 6.12.

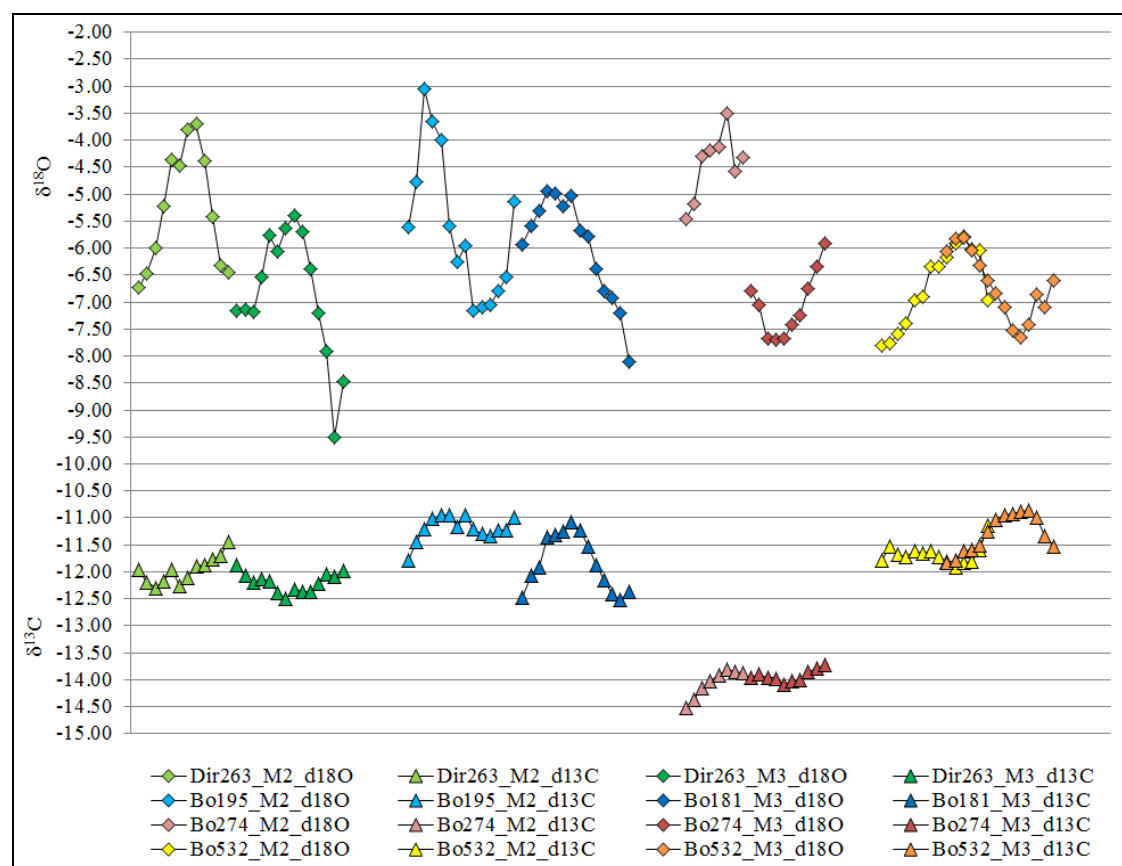


Fig. 6.12.  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  results of the sequentially sampled cattle molars.

The strontium isotope results have shown that most of the animals obtained food during enamel mineralisation from an area with a strontium signature consistent with the Upper Rhine Valley, except the individual from grave 274 from Bockenheim (see 5.2.4 and 7.1.1). The non-local character of this animal is also underlined by the differing  $\delta^{13}\text{C}$  values in comparison to the  $\delta^{13}\text{C}$  values of the other samples (Fig. 6.12). For Boc532 no strontium isotope analysis was performed. The cattle teeth from

the graves 195 and 181 had an almost identical  $^{87}\text{Sr}/^{86}\text{Sr}$  value which strengthens the assumption that the teeth are from a single individual (Tab. 5.3).

The  $\delta^{18}\text{O}$  values including all sample points range from  $-9.4$  to  $-2.9\text{‰}$  with a mean of  $-6.1 \pm 1.2\text{‰}$ . The amplitude of variation within a single tooth is between  $1.8$  and  $4.2\text{‰}$ . All teeth show a pattern of cyclic variation reflecting the annual seasonal cycle. The  $\delta^{13}\text{C}$  values show a total range of  $-14.6$  and  $-11.0\text{‰}$  with a mean of  $-12.2 \pm 1\text{‰}$ . The amplitude of variation within a single tooth is between  $0.4$  and  $1.4\text{‰}$ . Two individuals (Boc195/181 and Boc274) show  $\delta^{13}\text{C}$  values reflecting the seasonal cycle with highest  $\delta^{13}\text{C}$  values in summer and the lowest in winter. These cattle were probably grazing in the same type of open environment throughout the year. The values in summer are higher as a result of decreased water availability. The other two individuals (Boc263 and Boc532) show the opposite trend with the lowest values in summer and the highest in winter. The reason for this could be a denser tree cover during summer time or the movement into shaded woodland from open grassland in the summer. The resulting canopy effect leads to a depletion of  $\delta^{13}\text{C}$  values. Furthermore, different plant species and different plant parts produce different  $\delta^{13}\text{C}$  values (Heaton 1999). Therefore, it may be that the pattern results from a seasonally varied diet involving the consumption of different species or plant parts available at different times of the year (Towers et al. 2010; Sjörgen/Price 2013).

The expected cyclic patterns of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values show that the samples are not diagenetically altered. Otherwise, there would be an averaging of the systematic variations (Sharp/Cerling 1998, 221–222; Knipper 2012, 154). The  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  investigations of the cattle teeth are not the focus of this study but for the sake of completeness the most important observations will be shortly reported here. Tab. 6.5 shows the results of the mean  $\delta^{18}\text{O}$  values of each tooth which are transformed into meteoric water values with the existing equations for cattle (for more details see Knipper 2011, 149–150; 296). The mean annual  $\delta^{18}\text{O}$  values measured in Koblenz between 1981 and 2005 are between  $-8.7\text{‰}$  and  $-5.7\text{‰}$  with a mean of  $-7.1\text{‰}$  and in Karlsruhe between  $-9.4\text{‰}$  and  $-6.7\text{‰}$  with a mean of  $-7.9\text{‰}$ . The calculated cattle samples are decreased in comparison to the measured  $\delta^{18}\text{O}$  values in precipitation. This is surprising as fractionations in leaf water and the evaporation of surface water results in the enrichment of  $\delta^{18}\text{O}$  values in drinking water in comparison to precipitation (Knipper 2011, 302). The most probable reason for the difference is equation errors (Pollard 2011b). This shows the weakness of the transformation from

$\delta^{18}\text{O}_{\text{cVPDB}}$  to  $\delta^{18}\text{O}_{\text{mwVSMOW}}$  values based on existing equations. Therefore, the discussion of the values should be based on raw data rather than transformed data.

**Tab. 6.5. Transformation of cattle mean  $\delta^{18}\text{O}_{\text{cVPDB}}$  values into  $\delta^{18}\text{O}_{\text{mwVSMOW}}$ .**

Sample	Tooth	$\delta^{18}\text{O}_{\text{cVPDB}}$	a) $\delta^{18}\text{O}_{\text{cVSMOW}}$	b) $\delta^{18}\text{O}_{\text{pVSMOW}}$	c) $\delta^{18}\text{O}_{\text{mwVSMOW}}$	d) $\delta^{18}\text{O}_{\text{mwVSMOW}}$	e) $\delta^{18}\text{O}_{\text{mwVSMOW}}$
Dir263	M2	-5.2	25.6	16.6	-8.1	-10.6	-13.8
Dir263	M3	-6.8	23.9	15.0	-9.7	-12.2	-15.4
Boc195	M2	-5.9	24.8	15.8	-8.8	-11.3	-14.5
Boc181	M3	-5.6	25.1	16.1	-8.5	-11.0	-14.2
Boc274	M2	-4.4	26.4	17.4	-7.3	-9.7	-12.9
Boc274	M3	-6.9	23.7	14.8	-9.9	-12.4	-15.6
Boc532	M2	-6.8	23.9	14.9	-9.7	-12.2	-15.4
Boc532	M3	-6.8	23.9	14.9	-9.7	-12.2	-15.4

a)  $\delta^{18}\text{O}_{\text{c(VSMOW)}} = 1.03091 \times \delta^{18}\text{O}_{\text{c(PDB)}} + 30.91$  (Hoefs 2009, 61)  
b)  $\delta^{18}\text{O}_{\text{p(VSMOW)}} = 0.98 \times \delta^{18}\text{O}_{\text{c(VSMOW)}} - 8.5$  (Iacumin et al. 1996)  
c)  $\delta^{18}\text{O}_{\text{mw(VSMOW)}} = \delta^{18}\text{O}_{\text{p(VSMOW)}} - 24.91/1.01$  (D'Angela/Longinelli 1990, 78)  
d)  $\delta^{18}\text{O}_{\text{mw(VSMOW)}} = \delta^{18}\text{O}_{\text{p(VSMOW)}} - 21.789/0.803$  (D'Angela/Longinelli 1990, Tab. V, Fig. 4)  
e)  $\delta^{18}\text{O}_{\text{mw(VSMOW)}} = \delta^{18}\text{O}_{\text{p(VSMOW)}} - 21.23/0.7$  (Hoppe 2006, 413)

The amplitudes of  $\delta^{18}\text{O}$  values of single teeth (between 1.8 and 4.2‰) are smaller than observed in precipitation (e.g. for Koblenz between -16.1 and -5.7‰ with a mean of -8.6‰ for the years 1981–2005). This is in accordance with other investigations observing a dampening of the seasonal signal (Balasse 2002; Passey/Cerling 2002; Balasse 2003; Kohn 2004; Passey/Cerling 2004; Podlesak 2008; Knipper 2011, 299). The probable reason is the averaging of isotope signals from a period longer than a month for each sample because of the delayed incorporation of oxygen isotopes from drinking water into tooth enamel, enamel maturation, the rough sampling technique or the mixing of different drinking water sources with different seasonal amplitudes (Knipper 2011, 299).

The mean  $\delta^{18}\text{O}$  differences between two teeth from a single individual are between 0.0 and 2.6‰. This is within the range of variation of mean  $\delta^{18}\text{O}$  differences between years in Koblenz, reaching differences up to 3‰. As calves are obtaining drinking (and plant) water early in addition to milk, a breastfeeding signal is not expected to be visible in the first half of the M2 which may be still influenced but is more likely to show the reflection of seasonal differences between single successive years (Bryant et al. 1994, 308–309; Higgins/MacFaden 2004, 342; Kohn et al. 1998; Knipper 2011, 151; 304).

## IV. DISCUSSION

### 7 Biogeochemical signatures of the Upper Rhine Valley

#### 7.1 Local strontium isotope range

##### 7.1.1 Archaeological faunal dental enamel and eggshells

One of the most recommended materials for the investigation of the local strontium range of a region are archaeological faunal teeth, provided the animals obtained food and drinking water locally and had the same food catchment area as the human community under study (Price et al. 2002b, 132; Bentley et al. 2004, 373; Evans/Tatham 2004, 244). Therefore, all available faunal teeth which were found within the graves during excavation of the three sites were sampled. As the number of available teeth from all three sites was relatively low ( $n = 22$ ), all teeth were analysed including those from cattle, pig, horse, sheep/goat and canid. A problem with most of these samples is the uncertain temporal context. Except for the horses, none of the remains can be assigned to the Early Medieval period with safety because they were found in the infillings of destroyed graves. In some cases, it is more probable that they are from an earlier temporal context because prehistoric or Roman remains were found within the infilling. In other cases, a modern context is more probable because of the good preservation in comparison to other animal remains from the same site. Some finds may be the buried remains of animals which were subject to emergency slaughter. The differing temporal context is not necessarily a disadvantage, as the animals could also have lived locally or were fed with locally produced fodder.

An additional problem with single teeth from pigs and canidae is that the remains are not necessarily from domestic species but could also be from wild boars or foxes. In these cases it is probable that they obtained food not only from the Upper Rhine Plain but also from the Palatinate Forest which would result in intermediate  $^{87}\text{Sr}/^{86}\text{Sr}$  values. This is probably the case for the pig tooth from grave 270 in Eppstein. This tooth was sampled at three positions (bulk-tip-cervix:  $^{87}\text{Sr}/^{86}\text{Sr}$  0.71042–0.71160–0.70993). The sample which was taken at the tip ( $^{87}\text{Sr}/^{86}\text{Sr}$  0.71160, 197 ppm) shows a similar  $^{87}\text{Sr}/^{86}\text{Sr}$  value and strontium concentration to one of the modern deer samples ( $^{87}\text{Sr}/^{86}\text{Sr}$  0.71144, 176 ppm) from the Palatinate Forest. Therefore, the pig sample will be excluded from the sample set which will be used to

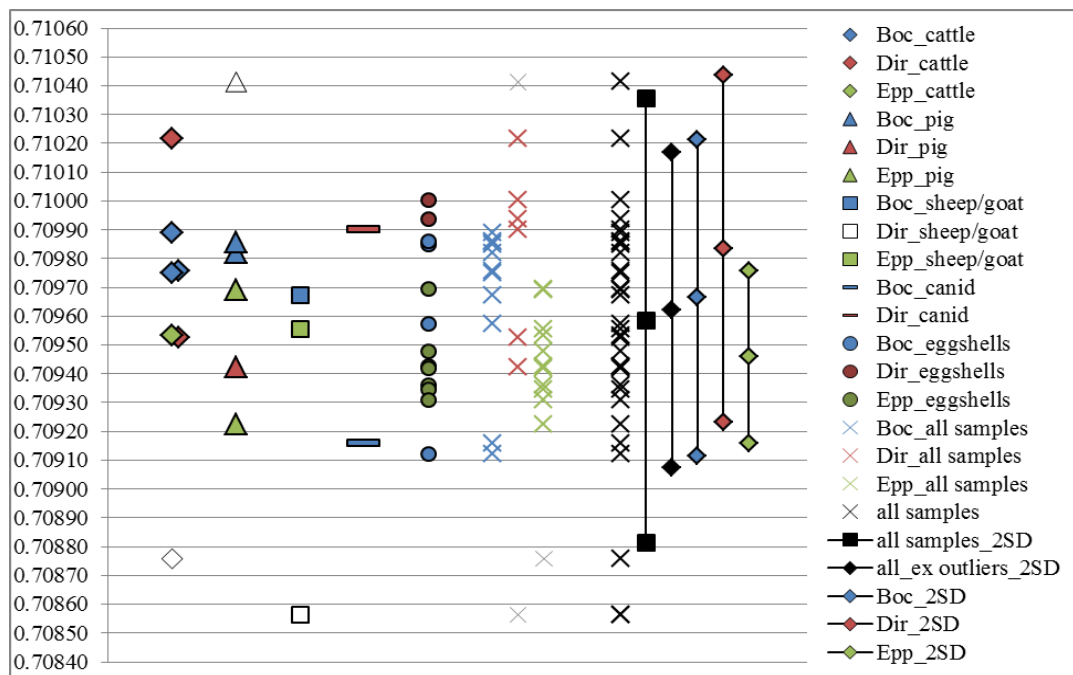
determine the local strontium range. This may also apply to the pig teeth from grave 230 in Dirmstein. This sample has the same  $^{87}\text{Sr}/^{86}\text{Sr}$  values (0.71041) as the bulk sample from the previously mentioned animal. However, the samples from grave 230 was not analysed sequentially and therefore it cannot be proved that this is not representative for the local range in Dirmstein but it should still be interpreted with caution. The other five pig teeth have  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios between 0.70923 and 0.70985. The canid tooth from Dirmstein was especially well preserved and is most probably from a modern context and should also be interpreted with caution. Due to the context of its discovery, the canid skeleton from Bockenheim is most probably from a dog that was buried together with a human funeral and it will therefore be used for the local strontium range.

Even if the horse remains are one of the only samples which can be assigned to the Early Medieval period with safety, they are generally not appropriate for estimation of the local range because of their mobile way of life. The horse tooth from Dirmstein was analysed sequentially and shows a large variability of values from the tip, to the middle, to the cervix. The horse tooth from Eppstein was only analysed as bulk but as the other sample has proven, this species is not usable and will be excluded.

Cattle as well as sheep/goat should be generally more appropriate for the estimation of the local range, provided they were kept in the proximity of the settlement and obtained local dietary sources. Cattle samples from all three sites show a large variability of  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios from 0.70876 to 0.71107. The most radiogenic value of a cattle sample from Bockenheim (grave 274) must be excluded. It deviates from the other cattle samples not only in the more radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  value and the slightly lower strontium concentration but also in lower  $\delta^{13}\text{C}$  values which indicates that this individual obtained food from another area.

The eggshells, which are most probably all deposited as food offering during the Early Medieval period, should be adequate for the estimation of the local range of a specific site. As domestic chicken were most probably held in the vicinity of the settlement with a narrow food catchment area it is likely that the  $^{87}\text{Sr}/^{86}\text{Sr}$  values show a small range which is specific for the site rather than the surrounding region. The shells which were identified as domestic chicken all show a restricted range between 0.70934 and 0.71000, whereas Dirmstein has the most radiogenic signals, followed by Bockenheim and then Eppstein. Three of the samples are identified as Anseriformes,

most probably goose. The two samples from Eppstein are not different from the domestic chicken samples but the one from Bockenheimer is slightly lower. This sample will not be excluded but should be taken with caution. Another eggshell sample from Bockenheimer could not be identified, either because the sample was too destroyed or the species was an exotic one (Stewart 2012, pers. comm.). The low value could indicate either contamination or different geological substrate and should be excluded from the local range estimation.



**Fig. 7.1. Faunal enamel and eggshell samples for the determination of the local range.**

The remaining 31 faunal dental enamel (bulk) and eggshell samples range between 0.70856 and 0.71041 with a mean of  $0.70958 \pm 0.00039$  ( $1\sigma$ ) (Fig. 7.1). Based on the traditional approach of calculating the mean  $\pm 2SD$ , the local strontium range is between 0.70881 and 0.71036. However, it is obvious that the cattle sample from Eppstein and the sheep/goat as well as the pig sample from Dirmstein are outliers because they differ more than 2SD from the mean. Excluding these samples, the local range is between 0.70907 and 0.71017 (mean  $\pm 2SD$ ,  $n = 28$ ). Dirmstein has the most radiogenic range (mean  $\pm 2SD$ : 0.70923–0.71044,  $n = 6$ ), followed by Bockenheimer (mean  $\pm 2SD$ : 0.70911–0.71021,  $n = 11$ ) and Eppstein (mean  $\pm 2SD$ : (0.70916–0.70976,  $n = 11$ ) (Fig. 7.1).



### 7.1.2 Human and faunal dentine and soil samples

The elevated strontium concentrations of the dentine samples in comparison with the respective enamel samples have clearly shown that the dentine samples are diagenetically altered by the incorporation of mobile strontium from the soil. However, dentine samples are problematic as they can overestimate the local range if samples of non-local individuals were used that have not completely taken the value of the burial soil. This is obviously the case for some of the samples (see Fig. 7.2). When these samples were excluded the mean  $\pm$  2SD is between 0.70908 and 0.71020 (mean: 0.70964,  $n = 34$ ) which is in good accordance with the local strontium range of 0.70907 and 0.71017 as determined by means of the faunal enamel and eggshell samples. The differences between the sites, which were already detected based on the faunal material, are also visible in the dentine samples. The human and faunal dentine samples from Bockenheim have a mean value of 0.70955 with a range between 0.70915 and 0.70995. Dirmstein has a mean value of 0.70990 with a local range between 0.70951 and 0.71030 and Eppstein has the lowest mean value of 0.70942 and the most restricted and least radiogenic local range between 0.70911 and 0.70972 (mean  $\pm$  2SD). The soil samples show more radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values than the enamel, dentine and eggshell samples. The reason for this is that they were treated with strong acids that also dissolved the heavily solving minerals in the soil. However, even if they cannot be used to determine the local strontium range, they confirm the small  $^{87}\text{Sr}/^{86}\text{Sr}$  differences between the sites.

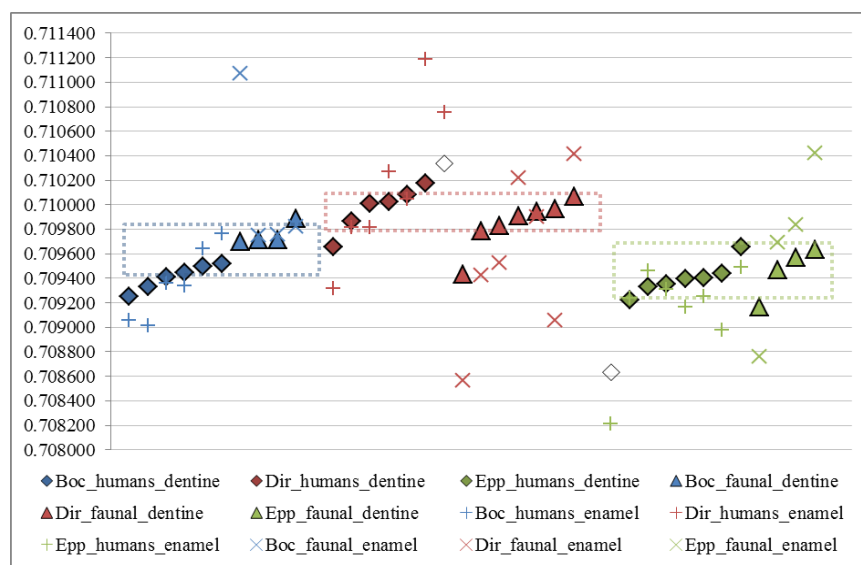


Fig. 7.2. Human and faunal dentine  $^{87}\text{Sr}/^{86}\text{Sr}$  values in comparison to enamel.

### 7.1.3 Human tooth enamel

The tooth enamel of children seems to be appropriate for estimating the local strontium range. With the exception of two outliers,  $^{87}\text{Sr}/^{86}\text{Sr}$  values of non-adult tooth enamel show a restricted strontium range at each cemetery and the local range calculated with the mean  $\pm$  2SD for all sites is 0.70915–0.71006. This is in good accordance with the local range based on faunal material (0.70907–0.71017) and the dentine samples (0.70908–0.71020). The differences between the sites are also visible in the  $^{87}\text{Sr}/^{86}\text{Sr}$  values of the children (Fig. 7.4). Contamination of children's teeth with soil strontium due to incomplete mineralisation is unlikely because the strontium concentrations are not increased in comparison to adult tooth enamel (mean tooth enamel children 127 ppm, mean tooth enamel adult 128 ppm).

All human tooth enamel samples were used in order to estimate the local range based on a statistical approach, excluding samples that do not contribute to a normal distribution. The range was estimated to be between 0.70861 and 0.71020. When comparing this range with those obtained by faunal material, dentine and children's enamel, it is most probable that this approach overestimates the local range because there are several data points which are outside the local range based on the more conservative approach. A better fit with the conservative approach is achieved with the method which calculates the differences between each sample after they were arranged in an ascending order. The determined range of 0.70898 to 0.71011 is only slightly larger than the local ranges which were calculated with the conservative method. There is also a good agreement in Eppstein (0.70898–0.70976) and Dirmstein (0.70944–0.70989). In Bockenheim, the lower limit of the range (0.70902) coincides but the upper limit of 0.70940 is too low; more accurate may be the second break at 0.70987, which fits well with the upper borders estimated by the conservative approach.

### 7.1.4 Water samples

Studies have shown that the  $^{87}\text{Sr}/^{86}\text{Sr}$  of water samples generally reflect their geological catchment area and have been successfully used to determine the local strontium signature of a region (Montgomery et al. 2006; Voerkelius et al. 2010; Frei/Frei 2011; Maurer et al. 2012). However, water samples can be influenced by anthropogenic pollutants or atmospheric inputs (Böhlke/Horan 2000; Probst et al.

2000; Négrel et al. 2000; Négrel et al. 2004; Christian et al. 2011). Otherwise, studies have shown that even in agricultural zones water is mainly dependent on bedrock geology (Semhi et al. 2000; Douglas et al. 2002; Frei/Frei 2011; Maurer et al. 2012). Investigations of groundwaters in Rhineland-Palatinate have shown that, especially in the area of the Upper Rhine Plain, waters are strongly anthropogenically polluted, mainly as a result of the intensive agricultural use of this region (Blitzer et al. 2012). In order to estimate the amount of pollutants (fertilisers, sewage effluents, animal manure etc.) in the surface water it is necessary to know the strontium isotopic composition and concentration of strontium in the different compounds (Frei/Frei 2011, 336); these data are lacking for the study area. Fertilisers used in Spain show  $^{87}\text{Sr}/^{86}\text{Sr}$  values between 0.70340 and 0.71520 with the majority between 0.70800 and 0.70900 (Vitòria et al. 2004). The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of anthropogenic sources such mineral fertiliser, sewage, and animal manure in France vary from 0.70788 to 0.71155 (Négrel 1999, 155; Widory et al. 2004, 175; Négrel et al. 2004, 966). These few examples show that there may be a large overlap between  $^{87}\text{Sr}/^{86}\text{Sr}$  of pollutants and the local strontium signature of the Upper Rhine Valley and that this topic cannot be solved without measuring the potential local pollutants. However, based on the results of the water samples, in combination with the hydrochemical map, some observations can be made. The three samples which were taken from the Isenach stream clearly show a decreasing trend in  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios and an increasing trend in strontium concentrations from the first sampling location at the Isenachweiher in the Buntsandstein area of the Palatinate Forest, to the sample taken on Pliocene-Quaternary terrace sediments, to the last location in the near of Eppstein on Quaternary sediments of the older Rhine terrace. A scatter plot presenting  $^{87}\text{Sr}/^{86}\text{Sr}$  versus  $1/\text{Sr}$  concentration shows that these samples almost build a straight line (Fig. 7.3). This can mean that the strontium isotopic composition of water is controlled by the weathering of two end-members (Maurer et al. 2012, 224). In the case of the Isenach this could reflect the mixing of radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  from the Buntsandstein area and non-radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  from Pliocene-Quaternary sediments. However, as the Isenach is the most polluted river of the northern Upper Rhine Plain, the mix includes also  $^{87}\text{Sr}/^{86}\text{Sr}$  from anthropogenic sources. In how far they are influencing the strontium isotopic composition cannot be stated.

The stream water samples which were taken in the vicinity of the site of Eppstein have a  $^{87}\text{Sr}/^{86}\text{Sr}$  value of 0.71010. The local range of this site does not

exceed 0.70980 (see 7.1.6). This offset can mean that the water is either influenced by contaminants with a more radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  value or by more radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  from the Buntsandstein area.  $^{87}\text{Sr}/^{86}\text{Sr}$  of the faunal and human samples, as well as the soil (as reflected by the dentine samples), could be less radiogenic because animals and humans obtained most of their strontium from near-surface, upper soil horizons and through shallow rooted plants with less radiogenic strontium ratios in comparison to contaminated or stream water which obtains strontium mainly at deeper soil levels.

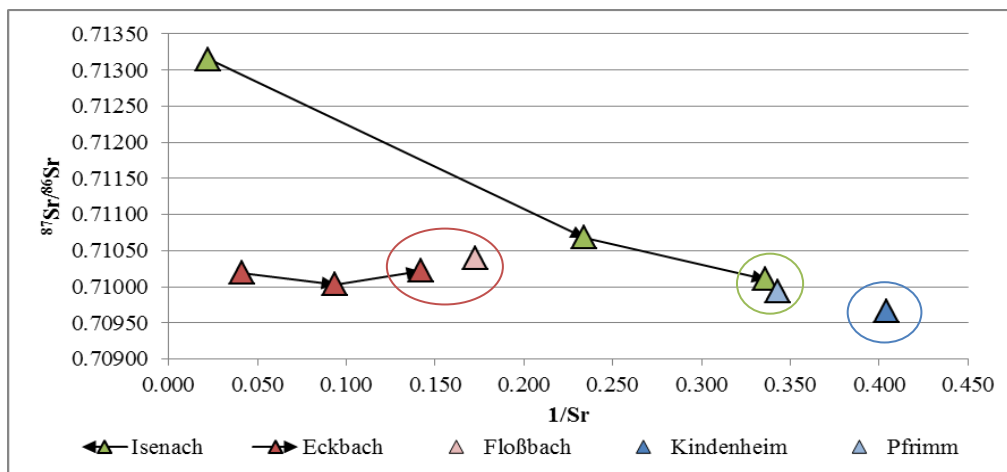


Fig. 7.3. Scatter plot of  $^{87}\text{Sr}/^{86}\text{Sr}$  versus  $1/\text{Sr}$  concentration for stream water samples.

At Dirmstein there is not such a large offset between water samples and local range, but the water samples are at the upper limit of the local range (local value at maximum 0.71040; water samples 0.71040 and 0.71022). The  $^{87}\text{Sr}/^{86}\text{Sr}$  values of the three samples from the Eckbach stream are very similar, between 0.71003–0.71022, and the strontium concentration increases only slightly from 96 ppm in the Buntsandstein area, to 209 ppm in the area of Tertiary sediments, to more than 300 ppm on Pliocene-Quaternary sediments. The mixing relation which was seen in the water samples of the Isenach is lacking. In fact, the sample which was taken in the vicinity of Dirmstein is slightly decreased in comparison to the samples from the Buntsandstein area. Most probably the samples reflect a mixture of  $^{87}\text{Sr}/^{86}\text{Sr}$  from their geological catchment area and  $^{87}\text{Sr}/^{86}\text{Sr}$  from polluted waters. The sample from the Buntsandstein area was taken in an area which was already used by industry and may be polluted by industrial waste water.

The water samples which were taken in the vicinity of the site of Bockenheim have slightly less radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures in comparison to the southern streams. There is no offset between the determined local range of Bockenheim

(0.70900 to 0.71020) and the water samples (0.70966 to 0.70994). The less radiogenic values are most probably a reflection of the local geological catchment area. The Kindenbach stream originates only a few kilometres away from the site of Bockenheim, in a region characterised by Tertiary carbonates. Anthropogenic influence in this agriculturally-used area is also probable. Even if the exactness of the hydrochemical map is not clearly proven, especially the borders, it can be tentatively stated that stream waters which are influenced by Tertiary sediments are slightly decreased in comparison to those influenced by Pliocene to Quaternary sediments. In addition, stream water sampled in the Buntsandstein area is also elevated but the mixing with Tertiary and Quaternary sediments or polluted waters decreases the strontium signature very quickly. However, even if the water samples clearly show trends which reflect the geological catchment area of the stream, they will not be used for the estimation of the local range because of the uncertainties concerning anthropogenic influence and the mixing of different strontium sources.

#### 7.1.5 Deer samples

The three modern deer tooth enamel samples have  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures between 0.71144 and 0.71376 which is in good accordance with the unpolluted water sample from the Isenachweiher, with a  $^{87}\text{Sr}/^{86}\text{Sr}$  value of 0.71315, situated on the same geological unit. One of the three deer samples has a slightly decreased  $^{87}\text{Sr}/^{86}\text{Sr}$  signature and increased strontium concentration in comparison to the others. The reason may be that this individual obtained some amounts of food from the Upper Rhine Plain during tooth formation. However, the complete range of analysed  $^{87}\text{Sr}/^{86}\text{Sr}$  values from 0.71144 to 0.71376 is in good agreement with other samples measured on Buntsandstein areas in Southwest Germany, France and northern Switzerland, such as stream water (Durand et al. 2005), ground water (Aquilina et al. 1997; Horwath 2000; Matter et al. 1987; Ufrecht/Hölzl 2006), rock and minerals from fracture fillings (Matter et al. 1987; Nollet 2006) as well as plant and snail samples (Bentley et al. 2003; Oelze et al. 2012a). The mean  $^{87}\text{Sr}/^{86}\text{Sr}$  values of these studies are between 0.71300 and 0.71500, and all measurements except for a few data points are above 0.71000 (Knipper 2011, 244–245; 246, Fig. 9.24). In contradiction are the reported  $^{87}\text{Sr}/^{86}\text{Sr}$  values from snail shells from the Enztal, with a mean of  $0.70956 \pm$

0.00109 which are most probably anthropogenic influenced (Bentley et al. 2003, 475, Tab. 1; Knipper 2011, 245).

### 7.1.6 Comparison and conclusion

Fig. 7.4 summarises all approaches and materials which are used in this study in order to determine the local  $^{87}\text{Sr}/^{86}\text{Sr}$  range of the western side of the northern Upper Rhine Valley, excluding water and soils samples. Furthermore, published  $^{87}\text{Sr}/^{86}\text{Sr}$  values from other studies of the research area are also included.

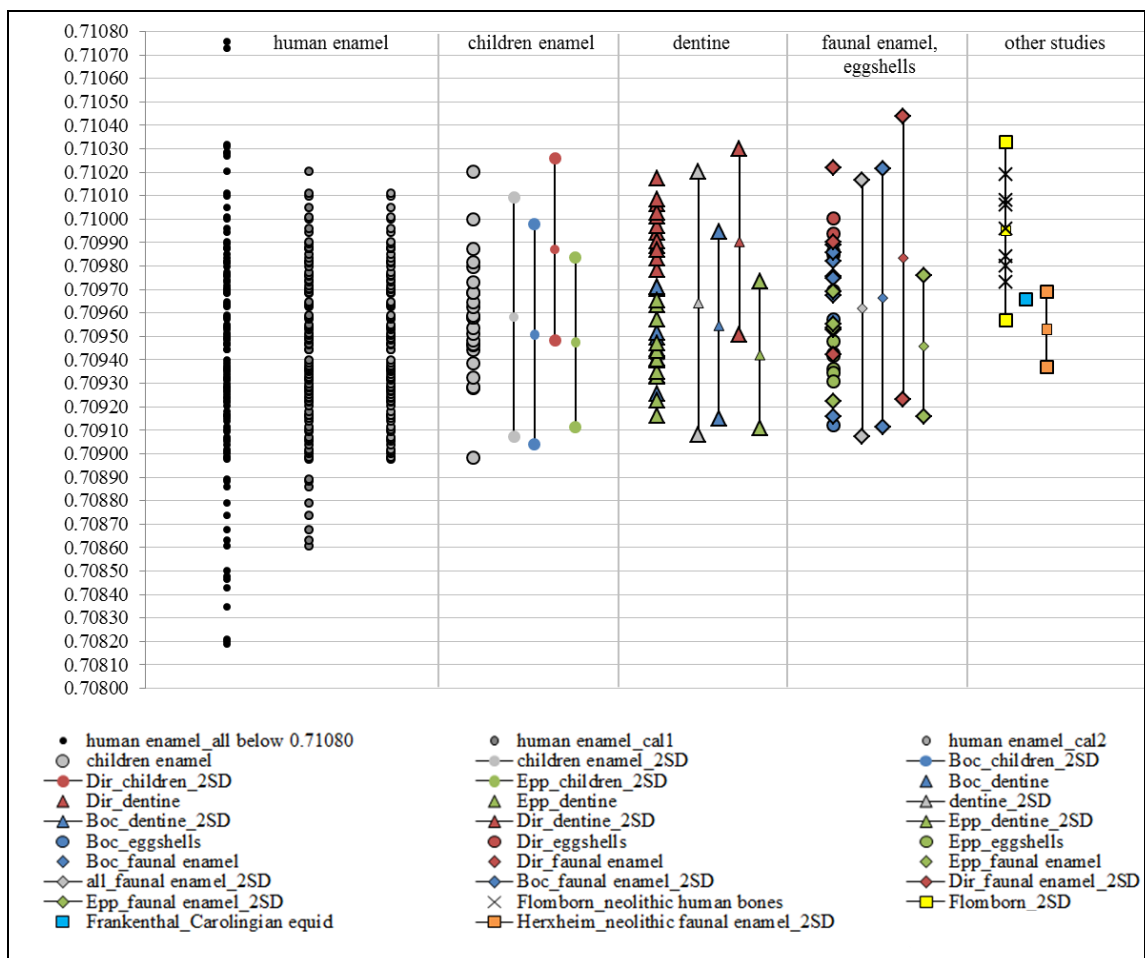


Fig. 7.4. Summary of the approaches and materials for estimating the local  $^{87}\text{Sr}/^{86}\text{Sr}$  range.

The graphic shows that none of the estimated ranges exceed the range of 0.70900 and 0.71050. This is also the case for the samples and ranges from other studies in the research area. Only the approaches which are based on the complete human enamel set (cal1 and cal2) exceed the lower limit of 0.70900. This is especially the case for the method where the sample set is compared to a normal distribution. Several samples below 0.70890 were included that are most probably outside the local

range. More difficult to interpret are the samples between 0.70898 and 0.70904 ( $n = 6$ ) which are outside the local  $^{87}\text{Sr}/^{86}\text{Sr}$  range estimated by the conservative method ( $\text{mean} \pm 2\text{SD}$ ) using enamel from children, faunal material and dentine; the difference is so small, that these values can only be discussed in connection with the other isotopes and the archaeological evidence. When viewed in more detail, it can be seen that the ranges which are calculated based on the  $\text{mean} \pm 2\text{SD}$  from enamel of children, dentine, as well as faunal enamel and eggshells from all three sites (grey points) are very similar and range between 0.70910 and 0.71020. Considering the ranges of each category for each site, it can be seen that there are slight differences between the locations. Eppstein (green) shows the most restricted range in all categories, which is between 0.70910 and 0.70980. Bockenheim (blue) has a range between 0.70900 and 0.71020, and Dirmstein (red) has the most radiogenic range between 0.70920 and 0.71040.

## 7.2 Local oxygen isotope signatures

The determination of the local oxygen range is more complicated than the estimation of the local strontium signature because oxygen is shaped by more variables and prone to error when using conversion equations. The most secure way to calculate the oxygen range is by means of the samples under study that show a local strontium signature. As it was shown that deciduous teeth and permanent teeth forming during the time when a child is nursed are in several cases enriched in  $\delta^{18}\text{O}$ , they have to be excluded. When only those P2, M2 and M3 were included which show a local strontium value approximately between 0.70900 to 0.71000, the mean  $\delta^{18}\text{O}$  is  $-4.3 \pm 0.7\text{‰}$  ( $n = 58$ ) with values ranging between  $-2.3$  and  $-5.7\text{‰}$ . Ranges between 0.6 up to 2‰ have been reported as representative of a sedentary group sharing a single water source in phosphate  $\delta^{18}\text{O}$  values (Longinelli 1984; White et al. 1998; Daux et al. 2008; McManus et al. 2013; White 2013). Therefore, the amplitude of  $-3.4\text{‰}$  is too large. Furthermore, it is highly probable that the local strontium range of 0.70900 and 0.71000 includes individuals that are not local based on their oxygen isotopic composition. This is obviously the case, as several individuals are outside 2SD from the mean value of  $-4.3\text{‰}$ . When these samples were stepwise excluded, the mean  $\delta^{18}\text{O}$  is  $-4.4 \pm 0.4\text{‰}$  ( $n = 49$ ) with values ranging between  $-3.5\text{‰}$  and  $-5.2\text{‰}$  (see Tab. 10.9). This range is consistent for each site (Bockenheim: range =  $-5.1$  to

$-3.8\text{‰}$ ;  $-4.3 \pm 0.4\text{‰}$ ,  $n = 11$ ; Dirmstein: range =  $-4.9$  to  $-3.7\text{‰}$ ;  $-4.5 \pm 0.3\text{‰}$ ,  $n = 16$ ; Eppstein: range =  $-5.2$  to  $-3.5\text{‰}$ ;  $-4.3 \pm 0.5\text{‰}$ ,  $n = 22$ ). The amplitude of  $-1.7\text{‰}$  is within the upper limit of reported ranges for a community using a common water source (Longinelli 1984; White et al. 1998; Daux et al. 2008; McManus et al. 2013; White 2013).

In order to test if this range is consistent with measured  $\delta^{18}\text{O}$  of meteoric or drinking water ( $\delta^{18}\text{O}_{\text{dw}}$ ), the values were converted with the following equations:

$$(1) \quad \delta^{18}\text{O}_{\text{cVSMOW}} = 1.03091 \times \delta^{18}\text{O}_{\text{cVPDB}} + 30.91 \quad (\text{Coplen et al.})$$

$$(2) \quad \delta^{18}\text{O}_{\text{pVSMOW}} = 1.0322 \times \delta^{18}\text{O}_{\text{cVSMOW}} - 9.6849 \quad (\text{Chenery et al. 2012})$$

$$(3) \quad \delta^{18}\text{O}_{\text{dwVSMOW}} = 1.54 \times \delta^{18}\text{O}_{\text{pVSMOW}} - 33.72 \quad (\text{Daux et al. 2008})$$

The calculated  $\delta^{18}\text{O}_{\text{dw}}$  of the estimated local range is  $-8.0$  to  $-5.3\text{‰}$  (corresponding to  $\delta^{18}\text{O}_{\text{cVPDB}} -3.5$  to  $-5.2\text{‰}$ ) with a mean of  $-6.7 \pm 0.7\text{‰}$  (corresponding to  $\delta^{18}\text{O}_{\text{cVPDB}} -4.4 \pm 0.4\text{‰}$ ). When comparing this range to the weighted annual mean  $\delta^{18}\text{O}$  of precipitation recorded at the IAEA stations at Koblenz and Karlsruhe which are  $-7.1 \pm 0.7\text{‰}$  ( $1\sigma$ ) and  $-7.9 \pm 0.7\text{‰}$  ( $1\sigma$ ) respectively, the  $\delta^{18}\text{O}_{\text{mw}}$  calculated from the human tooth enamel is increased in comparison to  $\delta^{18}\text{O}_{\text{mw}}$ . There are several causes which may contribute to this difference, such as pretreatment, measurement, standards, conversion error, diagenesis or climatic change. In addition, M2 and P2 can be still influenced by a slight breastfeeding effect. However, even if none of these can be completely excluded, it is nevertheless more probable that human cultural habits or additional evaporation processes are responsible for the differences. A possible cause for enriched  $\delta^{18}\text{O}$  values is evaporative enrichment of shallow well water, but more likely is the consumption of heated foods. Hot drinks raise the local drinking water  $\delta^{18}\text{O}$  value by an average of  $0.4\text{‰}$ , and soups and stews by as much as  $11.9\text{‰}$  (Brettell et al. 2012b). Furthermore, the contribution of raw and cooked meats, vegetables, and grains to human diet suggest an overall  $\delta^{18}\text{O}_{\text{p}}$  enrichment ranging from  $0.6$  to  $0.7\text{‰}$  but not exceeding  $1.1\text{‰}$  in human tooth enamel (Daux et al. 2008). When adding an enrichment of  $0.7\text{‰}$  to the sample set, the mean  $\delta^{18}\text{O}$  of human tooth enamel is  $-7.4\text{‰} \pm 0.7\text{‰}$  and is in good accordance with the measured mean  $\delta^{18}\text{O}$  values in Koblenz and Karlsruhe. A comparable enrichment of  $0.9\text{‰}$  was also found in human tooth enamel of another early medieval site, the Anglo-Saxon cemetery of Berinsfield in England, which was also interpreted as enrichment as a result of human cultural behaviour (Hughes et al. 2014). However, while the mean value fits with the



measured  $\delta^{18}\text{O}$  values of Karlsruhe and Koblenz, the estimated local range of between  $-8.7\text{‰}$  and  $-6.0\text{‰}$  is too large and spans the complete range of measured  $\delta^{18}\text{O}$  values in Northern and Central Europe (Fig. 7.5). Therefore, it is more realistic to estimate the local  $\delta^{18}\text{O}_{\text{dw}}$  range with a more conservative range of  $\pm 1\text{‰}$  ( $-7.4\text{‰} \pm 0.5\text{‰}$ ) which results in a local  $\delta^{18}\text{O}_{\text{dw}}$  range approximately between  $-7.9$  and  $-6.9\text{‰}$ .

The preceding statements clearly show the problems which are connected with estimation of the local  $\delta^{18}\text{O}$  range of a region. For the discussion of  $\delta^{18}\text{O}$  values for the human individuals in the following chapter, the raw  $\delta^{18}\text{O}_{\text{C VPDB}}$  data will be used. The maximum local range will be  $-3.5\text{‰}$  to  $-5.2\text{‰}$  and the minimum local range will be estimated by the mean  $\delta^{18}\text{O}_{\text{C VPDB}}$  value of each site  $\pm 0.5\text{‰}$  (Bockenheim:  $-4.8$  to  $-3.8\text{‰}$ ; Dirmstein:  $-5.0$  to  $-4.0\text{‰}$ ; Eppstein:  $-4.8$  to  $-3.8\text{‰}$ ). In order to make the values comparable to other studies and the  $\delta^{18}\text{O}_{\text{dw}}$  distribution maps as in Fig. 7.5 the data will be transformed with the formulas described above. When comparing with modern drinking water values, a correction of  $0.7\text{‰}$  will be included. The corresponding values will be presented in brackets after the original  $\delta^{18}\text{O}_{\text{C VPDB}}$  value.

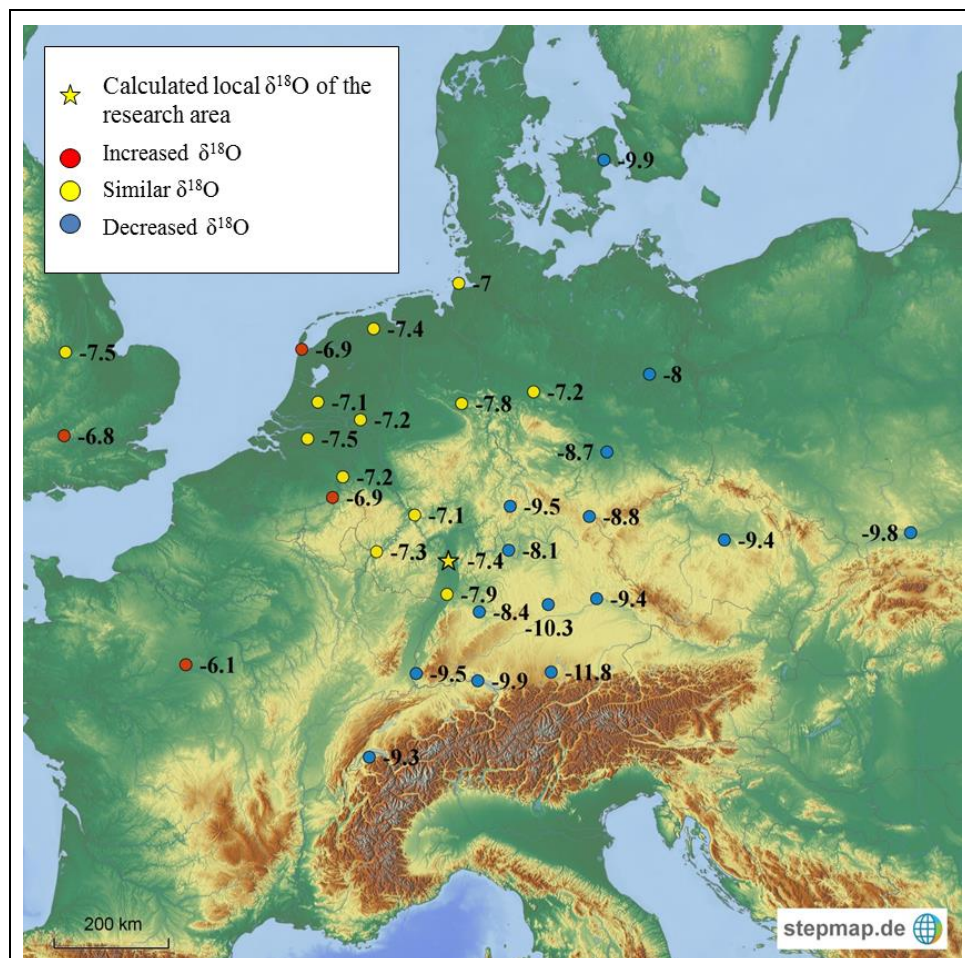


Fig. 7.5. GNIP  $\delta^{18}\text{O}$  values from Western and Central Europe (data from IAEA/WMO 2006).

### 7.3 Local carbon isotope signatures

The determination of the local carbon isotope range is less complicated because it can be expected that the range matches the range of a C<sub>3</sub> plant based terrestrial ecosystem. Modern C<sub>3</sub> plants exhibit a range of  $\delta^{13}\text{C}$  values between  $-37.0$  to  $-20.0\text{‰}$  ( $-31.5$  to  $-23.0\text{‰}$ ) with an average value clustering around  $-26.5$ / $-28.5\text{‰}$  (Kohn 2010, 2). When including an atmospheric offset between modern and pre-industrial values of  $1.5\text{‰}$  and an offset between human diet and enamel bioapatite of at least  $11.5\text{‰}$ , the local  $\delta^{13}\text{C}$  range should be within the range of  $-24.0$  to  $-7.0\text{‰}$  ( $-18.5$  to  $-10\text{‰}$ ) with values clustering mainly around  $-13.5$ / $-15.5\text{‰}$ . The  $\delta^{13}\text{C}$  range for all 137 human tooth enamel samples is between  $-15.1$  and  $-9.7\text{‰}$  with a mean of  $-13.3 \pm 0.9\text{‰}$  ( $1\sigma$ ) and is therefore within the range of a C<sub>3</sub> terrestrial based diet. When only those individuals with a local strontium and oxygen signature, the range is between  $-14.3$  and  $-10.4\text{‰}$  with a mean of  $-13.3 \pm 0.7\text{‰}$  ( $1\sigma$ ,  $n = 49$ ). The range is consistent for each site (Bockenheim: mean =  $-13.1 \pm 1.0\text{‰}$ ,  $n = 11$ ; Dirmstein: mean =  $-13.4 \pm 0.5\text{‰}$ ,  $n = 16$ ; Eppstein: mean =  $-13.4 \pm 0.7\text{‰}$ ,  $n = 22$ ). When excluding stepwise all samples outside the 2SD, the range changes only slightly and is between  $-14.2$  and  $-12.8\text{‰}$  with a mean of  $-13.5 \pm 0.4\text{‰}$  ( $1\sigma$ ,  $n = 41$ ). The range is consistent for each site (Bockenheim: range =  $-13.6$  to  $-12.8\text{‰}$ ; mean =  $-13.3 \pm 0.3\text{‰}$ ,  $n = 9$ ; Dirmstein: range =  $-14.0$  to  $-13.0\text{‰}$ ; mean =  $-13.5 \pm 0.3\text{‰}$ ,  $n = 15$ ; Eppstein: range =  $-14.2$  to  $-12.8\text{‰}$ ; mean =  $-13.5 \pm 0.4\text{‰}$ ,  $n = 17$ ).

When comparing the range of this study with that of the early medieval site of Wenigumstadt (Vohberger 2010, 120), it can be detected that the values of the Upper Rhine are slightly elevated and that the range of values and the standard deviation is larger (Wenigumstadt: range =  $-15.2$  and  $-12.0\text{‰}$ ; mean =  $-13.7 \pm 0.6\text{‰}$ ,  $n = 182$ ; Upper Rhine: range =  $-15.1$  and  $-9.7\text{‰}$ ; mean =  $-13.3 \pm 0.9\text{‰}$ ,  $n = 137$ ). This is also the case when only those samples were included with a local strontium value (Wenigumstadt: range =  $-15.2$  and  $-12.7\text{‰}$ ; mean =  $-13.8 \pm 0.6\text{‰}$ ,  $n = 94$ ; Upper Rhine: range =  $-14.3$  and  $-10.4\text{‰}$ ; mean =  $-13.3 \pm 0.7\text{‰}$ ,  $n = 49$ ), although the sample size for the Upper Rhine area is smaller than for Wenigumstadt. While the offset towards decreased values in Wenigumstadt is the result of different preparation or measurement techniques, the large range of values and larger standard deviation in the Upper Rhine Valley is striking. Unfortunately, no other studies are known which investigate tooth enamel apatite of contemporary samples from Central Europe. Other

studies with contemporary samples analysed bone collagen which is routed by different amounts of dietary components, mainly proteins, and are therefore not directly comparable to the sample set of this study.

However, even if all samples cluster within a typical range for a C<sub>3</sub> plant based diet, a few individuals have elevated  $\delta^{13}\text{C}$  values outside the 2SD above  $-11.5\text{‰}$  (n = 7). The reason for these elevated values may be the consumption of C<sub>4</sub> plants or animals which had eaten C<sub>4</sub> plants, an increased consumption of fish, or an origin from a C<sub>3</sub> ecosystem which has generally higher  $\delta^{13}\text{C}$  values than the Upper Rhine Valley as a result of lower mean annual precipitation and higher temperatures or higher altitude.

## 8 Sites

### 8.1 Eppstein

The general aim of the strontium, oxygen and carbon isotopic analysis of human tooth enamel of the early medieval cemetery of Eppstein is the identification of non-local individuals in order to explore the dynamics of the burial community from the late 5<sup>th</sup> century and during the 6<sup>th</sup> century. In the following, the different periods will be discussed in the light of the specific research questions described in 3.2.4.

#### *The founder graves*

The main research question concerning the founder graves at Eppstein was to evaluate if local communities were involved in the foundation of a new burial rite or if this was exclusively connected to the immigration of newcomers. Furthermore, it will be investigated how far the “multicultural” character of the grave goods is also reflected in the isotopic data. An overview of the results of the strontium and oxygen isotopic analysis is presented in Fig. 8.1.

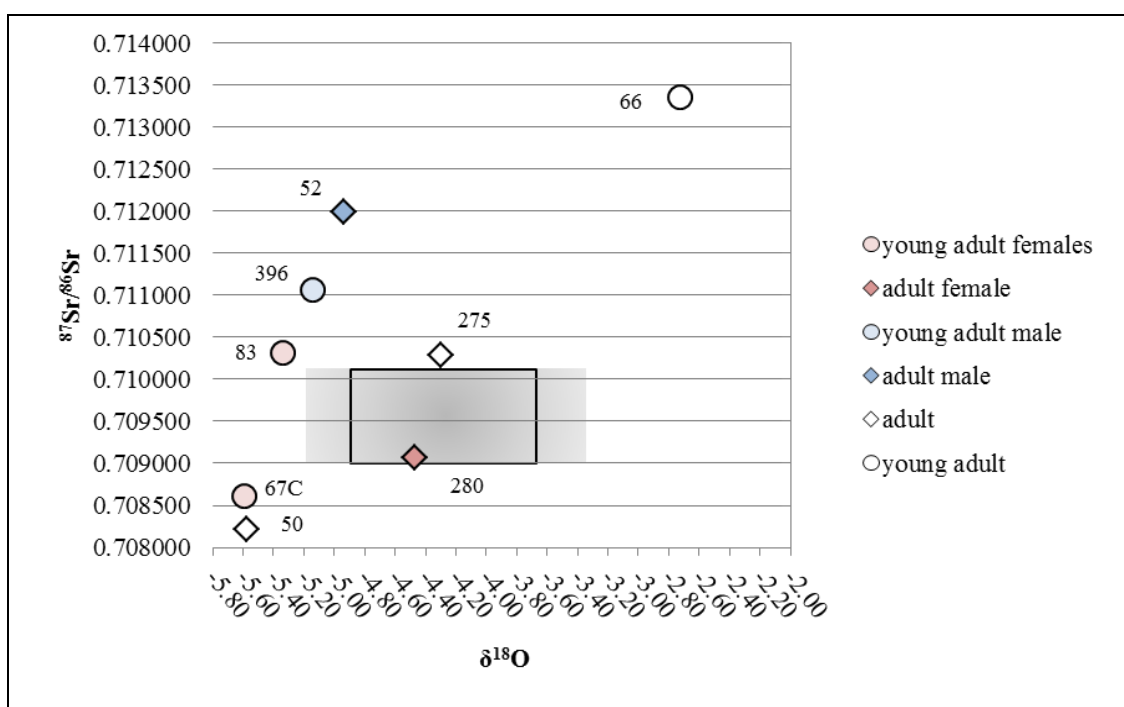


Fig. 8.1. Eppstein  $^{87}\text{Sr}/^{86}\text{Sr}$  vs.  $\delta^{18}\text{O}$  (SD-phases 2, 2–3, 3).

The individuals of graves 67C and 50 have  $^{87}\text{Sr}/^{86}\text{Sr}$  values of 0.70861 and 0.70821 respectively as well as quite consistent  $\delta^{18}\text{O}$  values of  $-5.6\text{‰}$  ( $\delta^{18}\text{O}_p \sim 16.3\text{‰}$ ;  $\delta^{18}\text{O}_{\text{dw}} \sim -8.6/-9.3\text{‰}$ ) (for conversion details see chapter 7.2) and are therefore

outside the local range for both isotope systems. While the  $\delta^{13}\text{C}$  values of the individual from grave 67C is within the normal range, the  $\delta^{13}\text{C}$  value of the person from grave 50 is elevated and has the highest  $\delta^{13}\text{C}$  value ( $-9.7\text{‰}$ ) of all analysed individuals from all three cemeteries. The undestroyed grave 50 belongs to an adult person of unknown sex. This poorly equipped grave only contained a small hand-made ceramic beaker with grooved decoration (*Rillenbecher*), a possible food offering as indicated by a charred piece of non-identifiable animal bone and a buckle. The hand-made beaker belongs to Terra Nigra-derivates which is distributed from south of the Danube River to the Lower Rhine Valley and dates the grave to the second half of the 5<sup>th</sup> century (Gross 1993; Engels 2012, 135–137). The destroyed primary grave 67C of a young woman contained a zoomorphic brooch, pearls from a necklace, a silver finger ring and a whorl. The little rabbit brooch and the finger ring are viewed in a Roman-Mediterranean cultural context and are interpreted as indirect proof of the presence of late Roman provincial communities (Engels 2005a, 328; Engels 2012, 211). Due to the more negative  $\delta^{18}\text{O}$  values an origin from an upland area is likely for both individuals. Lowland areas west of the northern Upper Rhine Valley such as the Netherlands, Belgium, France, and England can be excluded because similar or slightly higher  $\delta^{18}\text{O}$  values than in the Upper Rhine Valley are more common (see Fig. 7.5). Strontium values between 0.70820 and 0.70860 are typical for areas of Muschelkalk and Keuper (Matter et al. 1987; Horwath 2000; Ufrecht/Hölz 2006, Bentley/Knipper 2005; Tütken et al. 2006; Tütken 2008; Knipper 2011; Knipper et al. 2012; Maurer et al. 2011) but have also been measured in regions with Rotliegend (Knipper et al. 2014). The nearest region with less radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values and decreased  $\delta^{18}\text{O}$  values is the Wetterau region (Knipper et al. 2014, 830, Fig. 5) but also the adjacent Saar-Nahe Basin might be a possible area of origin. The combination of less radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values and decreased  $\delta^{18}\text{O}$  values have also been measured in the Bronze Age burial community of Singen which are supposed to obtain their diet from the Hegau region and the western shores of Lake Constance (Oelze et al. 2012b). The mean  $^{87}\text{Sr}/^{86}\text{Sr}$  value of eight individuals was  $0.70830 \pm 0.00036$  ( $1\sigma$ ) and the mean  $\delta^{18}\text{O}_{\text{pVSMOW}}$  value was  $15.5 \pm 0.8\text{‰}$  ( $1\sigma$ ,  $n = 9$ ) (Oelze et al. 2012b). Similar values were measured from skeletal remains of a female individual from a burial of the 9<sup>th</sup> century from Zürich (Tütken et al. 2008b). The results of the  $\delta^{18}\text{O}$  isotope measurements of the Thuringian cemeteries of Obermöllern and Rathwitz are unfortunately not published yet (Knipper et al. 2012a). The elevated  $\delta^{13}\text{C}$  values of

−9.7‰ from the individual from grave 50 indicate the consumption of a proportion of C<sub>4</sub> plants or animals eating C<sub>4</sub> plants (or marine food). The consumption of C<sub>4</sub> plants has also been assumed for few individuals from Roman and early medieval cemeteries in Germany and Britain (Hakenbeck et al. 2010, Müldner et al. 2010, Pollard et al. 2011a). However, most of the data are from collagen and therefore not directly comparable with data from bioapatite. The only study that measured  $\delta^{13}\text{C}$  of structural carbonate of tooth enamel was from a Roman cemetery in Kent, Britain. The measured  $\delta^{13}\text{C}_{\text{CVPDB}}$  values of several teeth from one individual are between −7.0 to −7.6‰ and the corresponding bulk collagen  $\delta^{13}\text{C}$  value was −15.2‰ (Pollard et al. 2011a).

Grave 66 of the young adult person of unknown sex is completely destroyed and robbed. The only object which was found was a “Mediterranean” belt buckle (Engels 2012, 63; 292). The grave can only be dated roughly into the SD-phase 2–3. However, this type of buckle was probably rather in use in the SD-phase 3 (Engels 2012). While the  $\delta^{13}\text{C}$  value (−13.7‰) of the analysed tooth is within the normal range for a C<sub>3</sub>-terrestrial diet, the  $\delta^{18}\text{O}$  and  $^{87}\text{Sr}/^{86}\text{Sr}$  values are outstanding in comparison with the other individuals of this early period. The combination of a radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  value of 0.71336 with a high  $\delta^{18}\text{O}$  value of −2.7‰ ( $\delta^{18}\text{O}_{\text{p}} \sim 19.3\text{‰}$ ;  $\delta^{18}\text{O}_{\text{dw}} \sim -4.0/-4.7\text{‰}$ ) is singular, not only in comparison to the other analysed samples from Eppstein but also in comparison to Dirmstein and Bockenheim. Other individuals with such high  $\delta^{18}\text{O}$  value have less radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values (e.g. Boc466, Boc392; Boc482, Dir5 and Epp48). The tooth is classified as probably M2. However, even if it is a M1 and is influenced by a breastfeeding signal, the  $\delta^{18}\text{O}$  value is still high when including an increase of around  $0.7 \pm 0.5\text{‰}$  (White et al. 2000; Dupras/Tocheri 2007). Increased  $\delta^{18}\text{O}$  values are consistent with parts of the Iberian Peninsula, and the Mediterranean on the southern European and north African side (Evans et al. 2012, 761; Fig. 12) but are not as high as in arid areas like the Egyptian Nile Valley or Jordan (Iacumin et al. 1996b; White et al. 2004; Perry et al. 2011). Similar high  $\delta^{18}\text{O}$  values have been measured in human tooth enamel of individuals from prehistoric, Roman and early medieval sites in England (Budd et al. 2004; Eckardt et al. 2009). While the high  $\delta^{18}\text{O}$  values of prehistoric individuals in Monkton were explained as a result of warmer climate 5500 BP years ago (Budd et al. 2004, 132–133), the individuals from the Roman and early medieval cemeteries are supposed to have spent their childhood in Southern Europe,

the Mediterranean or North Africa (Budd et al. 2004, 134; Eckardt et al. 2009, 2822; Chenery et al. 2010, 158). Most of these individuals also have less radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values than the person from grave 66. Exceptions are an older male individual from the low social status Trentholme Drive cemetery in York, which is supposed to exhibit a mix of traits associated with “white” and “black” ancestry based on anthropomorphic assessments, and a young male individual from a Roman cemetery near Gloucester; both share the same  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\delta^{18}\text{O}$  composition as the individual from grave 66. As the  $^{87}\text{Sr}/^{86}\text{Sr}$  value is more radiogenic (0.71336) and not close to the modern seawater value of 0.70920, an origin near the coast, or terrains over Mesozoic sediments of marine origin, or more generally a diet with foods derived from coastal zones where marine strontium has a significant effect on biosphere  $^{87}\text{Sr}/^{86}\text{Sr}$ , can be excluded. The individual most likely spent their childhood in areas of Palaeozoic rocks which can be found in areas of warm climate in the southern or western Iberian Peninsula, the Mediterranean coast of Algeria and Morocco, or western Turkey (Chenery et al. 2010, 158–159).

The individuals from the graves 52 and 396 have  $^{87}\text{Sr}/^{86}\text{Sr}$  values (0.71199–0.71107) above the local range and their  $\delta^{18}\text{O}$  values ( $-4.9$  to  $-5.1\text{‰}$ ;  $\delta^{18}\text{O}_p \sim 16.7$  to  $17.0\text{‰}$ ;  $\delta^{18}\text{O}_{dw} \sim -7.5$  to  $-8.0\text{‰}$ / $-8.2$  to  $-8.7\text{‰}$ ) are slightly decreased with respect to the local  $\delta^{18}\text{O}$  signature. While the  $\delta^{13}\text{C}$  value of the individual from grave 396 is within the normal range ( $-13.6\text{‰}$ ), the person from grave 52 has a slightly decreased  $\delta^{13}\text{C}$  value of  $-14.87\text{‰}$ . As the investigated tooth is probably an M1, the decreased value could be the result of a breastfeeding effect. Therefore, both individuals obtained their food during tissue formation from a different area than the Upper Rhine Valley. The plundered grave 396 belongs to a juvenile male person which was only poorly equipped with a knife, comb, a cloverleaf jug (*Kleeblattkanne*) and a small ceramic beaker (*Rillenbecher*) which is a Terra Nigra-derivate typical for Southwest Germany. Grave 52 was also destroyed and contained the remains of an adult, probably male, individual with offerings such as a bag with a firesteel, flint, comb, and tweezers. Both graves are dated to the SD-phase 2 (Engels 2012, 198). Strontium values above 0.71110 are typical for regions with Buntsandstein and basement rock. They were measured in prehistoric human tooth enamel from sites in the Wetterau region (Nehlich et al. 2009; Knipper et al. 2014), in pig tooth enamel from the Odenwald region (Knipper/Bentley 2005) as well as in Neolithic human enamel from Eulau in the vicinity of Naumburg (Saale) in Saxony-Anhalt (Haak et al. 2008; Haak

et al. 2010; de Jong et al. 2010). Radiogenic strontium values were also measured in tooth enamel of humans from the early medieval sites of Rathewitz and Obermöllern in Saxony-Anhalt but these individuals were interpreted as non-local (Knipper et al. 2012a). However, the nearest possible area with appropriate strontium values for the individuals from the graves 52 and 396 is the adjacent upland area of the Palatinate Forest with Buntsandstein. Modern deer dental enamel, analysed in this study, have revealed  $^{87}\text{Sr}/^{86}\text{Sr}$  values between 0.71144 and 0.71376 (see chapter 7.1.5). In combination with the slightly decreased  $\delta^{18}\text{O}$  values, a more eastern area for the individuals from the graves 52 and 396 is most likely (see Fig. 7.5).

The individuals from the graves 275 and 83 have almost the same  $^{87}\text{Sr}/^{86}\text{Sr}$  values (0.71028 and 0.71031 respectively), which are slightly above the local strontium range of the Upper Rhine Valley. The  $\delta^{18}\text{O}$  value of the individual from grave 275 was within the local range, while the  $\delta^{18}\text{O}$  value of  $-5.3\text{‰}$  ( $\delta^{18}\text{O}_p \sim 16.5\text{‰}$ ;  $\delta^{18}\text{O}_{dw} \sim -8.3/-8.9\text{‰}$ ) of the individual from grave 83 is decreased. Grave 275 belongs to an adult person of unknown sex and was completely destroyed. The burial contained only a few grave goods such as a cloverleaf jug and a comb and was dated to the SD-phase 2. One peculiarity of this grave is the construction of a niche which is common for the Middle and Upper Elbe region; particularly for the Vinařice/Niemberger group (Engels 2005a, 329). The grave of the young woman of the SD-phase 3 from burial 83 was also heavily destroyed and plundered and only two brooches, a buckle, and a comb were preserved. The zoomorphic brooch with a dove is iconographically assigned to the Roman-Christian cultural sphere, with a parallel brooch in grave 189 of the cemetery Lavoye in the Meuse department in Lorraine in northeastern France (Engels 2005a, 329; Engels 2012, 211–212). The few remaining objects show that this young woman had a wealthy background. Possible areas of origin of these two individuals are difficult to evaluate because strontium values of around 0.71030 occur in several areas of Europe and can also be the result of the mixing of two endmembers. In the case of the individual from grave 275 it might be the case that this person spent parts of the childhood in the Upper Rhine area. For the woman from grave 83 an origin from an upland area can be assumed because of the decreased  $\delta^{18}\text{O}$  value.

Grave 280 which was strongly plundered belongs to an adult woman. The only remaining object was an imitation of a brooch of the Weimar/Arcy-Saint-Restitute type. The prototypes of these brooches can be found in northern Gaul and the



Thuringian area (Engels 2005; 329; Theune 2008, 255, Fig. 5; Engels 2012, 82–83; 211–212). Engels dates the grave to the SD-phase 2 with questionmark, but the SD-phase 3 is also possible. While the  $\delta^{18}\text{O}$  value of  $-4.5\text{‰}$  ( $\delta^{18}\text{O}_p \sim 17.5\text{‰}$ ;  $\delta^{18}\text{O}_{dw} \sim -6.8/-7.5\text{‰}$ ) is indistinguishable from the local range, the  $^{87}\text{Sr}/^{86}\text{Sr}$  value is at the lower limit for Eppstein. In this case, it cannot be clearly stated if she was of non-local origin. However, similar  $^{87}\text{Sr}/^{86}\text{Sr}$  values have been measured in more western upland areas such as northern Germany, Belgium, the Netherlands and northern France (von Carnap-Bornheim et al. 2007; Gillmaier et al. 2009; Smits et al. 2010; McManus et al. 2010; Vohberger 2010; Grupe et al. 2011; Degryse et al. 2012; Price et al. 2013) with similar  $\delta^{18}\text{O}$  values to the Upper Rhine Valley (see Fig. 7.5).

The multi-isotopic analysis of the founder graves from the cemetery of Eppstein has shown that most of the individuals did not spend their childhood or youth in the Upper Rhine Valley. Only two individuals show isotopic values indicating that they might have spent a part of their childhood or youth in the Upper Rhine Valley (graves 280 and 275). Based on the archaeological record it was assumed that the founder graves of the SD-phase 2–3 were comprised of a “multicultural” community with Roman, Alemannic and Thuringian cultural influences (Engels 2005a, 327–331; Engels 2012, 210–212). This heterogenous character can be confirmed by the isotopic data. There are at least four different groups detectable. The first group is reflected by graves 83, 396 and 52. They have more radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values than the Upper Rhine Valley which is typical for older geological units and, based on slightly decreased  $\delta^{18}\text{O}$  values, an origin from an upland and/or colder area can be assumed. For the young individual from grave 66 with a “Mediterranean” belt buckle, a Mediterranean origin is likely based on the increased  $\delta^{18}\text{O}$  value. An additional area of origin is reflected by graves 67C and 50, whose decreased  $\delta^{18}\text{O}$  values are typical for upland and colder areas. The less radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values have been measured in Keuper, Muschelkalk and Rotliegend. The nearest possible areas of childhood residence are therefore the Saar-Nahe region west of the Upper Rhine Valley and several areas east of the Rhine such as the Wetterau, but also more southern areas in the region of Lake Constance. This is also likely for the two adult individuals from graves 275 and 280 which have isotopic values similar to the Upper Rhine Valley. However, with their local  $\delta^{18}\text{O}$  values the individuals from the graves 280 and 275 can also originate from more western areas or areas with the same  $\delta^{18}\text{O}$  value than the Upper Rhine Valley. The results have

shown that local individuals that were born in the Upper Rhine Valley did not play a major role in the foundation of the cemetery Eppstein. How far the individuals with non-local isotopic values represent former federate soldiers of the Roman army or their descendants is difficult to answer, because the exact dating of the graves is unclear. However, based on the young age of most of the individuals, it is likely that these “foreign” individuals rather represent fresh immigrations to the Upper Rhine Valley.

#### *The early 6<sup>th</sup> century*

At the beginning of the 6<sup>th</sup> century (SD-phase 4 = ca. 510–530), the Upper Rhine Valley was under the influence of the Merovingian king Theuderic. It is generally assumed that at this time people were settled in the conquered areas to consolidate the power of the new ruler. The profusion of hand-made pottery of the 6<sup>th</sup> century that is known from several early medieval sites in the Upper Rhine Valley and other indications are seen as evidence of newcomers from Middle Germany (Wieczorek 1989; Bernhard 1997; Koch 2000; Riemer 2008; Engels 2005a, Grünewald/Koch 2009; Engels 2012; Koch 2012a). This is also assumed for the cemetery of Eppstein (Engels 2005a, 327–331; Engels 2012, 210–212). However, as there are already indications of immigration from these regions in the preceding periods, this immigration is not seen as a new influence at the beginning of the 6<sup>th</sup> century but rather a sign of continuity. The location of the graves also indicates that there was no hiatus between the founder graves and the graves of the early 6<sup>th</sup> century (Engels 2012, 198; 210–212). The reason for the lack of graves from the SD-phase 3 is rather the lack of good datable objects. This is also the reason why several graves cannot be assigned to a certain period with safety. From 22 individuals which are dated to the SD-phases 4 and 4–5, eleven individuals have been analysed. These are nine male and two female individuals. The main question concerning this period is evaluating whether continuity between the founder graves and the next generation of graves can be detected. An overview of the results of the strontium and oxygen isotopic analysis is presented in Fig. 8.2.

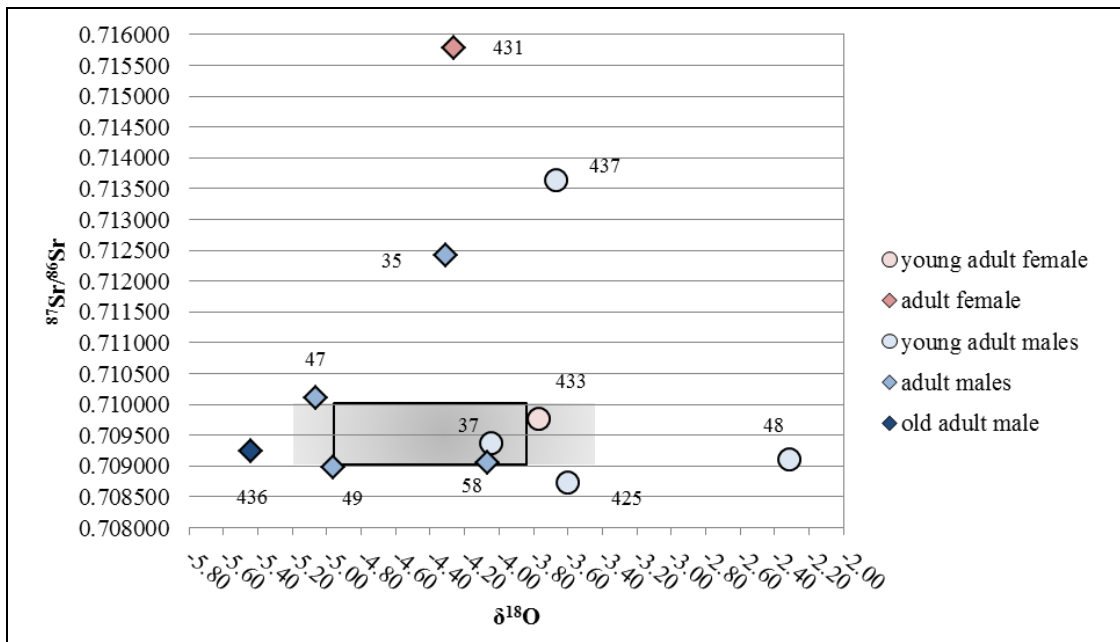


Fig. 8.2. Eppstein  $^{87}\text{Sr}/^{86}\text{Sr}$  vs.  $\delta^{18}\text{O}$  (SD-phases 4, 4-5).

The individuals from graves 431, 437 and 35 have  $^{87}\text{Sr}/^{86}\text{Sr}$  values above 0.71200 and are clearly outside the local strontium range. The  $\delta^{18}\text{O}$  of these individuals is indistinguishable from the local  $\delta^{18}\text{O}$  range. The  $\delta^{13}\text{C}$  values are within the range of a  $\text{C}_3$ -based terrestrial diet but the  $\delta^{13}\text{C}$  value of  $-10.9\text{‰}$  from the individual from burial 431 is more than 2SD increased from the mean, which may indicate a small proportion of a  $\text{C}_4$  component in the diet. The plundered grave 431 belongs to an adult female individual. There are no indications of a “foreign” origin for this woman based on her grave goods or the grave construction. A wheel-made ceramic vessel supports dating the grave to the SD-phase 4. The  $^{87}\text{Sr}/^{86}\text{Sr}$  value of 0.71578 is the most radiogenic of the complete sample set from Eppstein. Therefore, lowland areas with Cenozoic and Mesozoic sediments such as northern Germany, the Netherlands, western Belgium and large parts of northern France can be excluded as childhood residence places (von Carnap-Bornheim et al. 2007; Gillmaier et al. 2009; Smits et al. 2010; McManus et al. 2010; Vohberger 2010; Grupe et al. 2011; Degryse et al. 2012; Price et al. 2013). The adjacent Saar-Nahe hills and the Palatinate Forest can also be excluded because less radiogenic values are common in these regions. Strontium values above 0.71578 are typical for Palaeozoic sediments and metamorphic rocks (Voerlikus et al. 2010, Fig. 1). The young adult male from the undestroyed grave 437 was poorly equipped and only had objects such as a bronze and iron buckle, a sax knife, a comb, a firestone, a few metal tools, and a hand-made

imitation of early Frankish wheel-made pottery was found which dates the grave most probably to the SD-phase 4. The  $^{87}\text{Sr}/^{86}\text{Sr}$  value of 0.71364 is comparable to the founder generation individual from grave 66 with the “Mediterranean” belt buckle. The  $\delta^{18}\text{O}$  value of  $-3.7\text{‰}$  ( $\delta^{18}\text{O}_p \sim 18.3\text{‰}$ ;  $\delta^{18}\text{O}_{dw} \sim -5.5/-6.2\text{‰}$ ) is within the local range but towards the upper limit. The adult male from grave 35, which is dated to the SD-phase 4, was equipped with weapons, tools and a hand-made vessel with parallels to pottery from the cemeteries Schretzheim and Pleidelsheim in Baden-Württemberg. These vessels were connected with the immigration of individuals from Middle Germany (Engels 2012, 139; Koch 1977, 136–138). While the  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values are both local, the  $^{87}\text{Sr}/^{86}\text{Sr}$  is more radiogenic and comparable to grave 52 from SD-phase 2–3. These three individuals spent their childhood in a different area than the Upper Rhine Valley.

The heavily destroyed grave 48 belongs to a young adult male. The remaining graves goods such as a wheel-made pottery vessel, a comb and an arrowhead date this individual to the SD-phase 4. While the  $^{87}\text{Sr}/^{86}\text{Sr}$  value is rather in the upper limit of the local range, the  $\delta^{18}\text{O}$  value is strongly decreased with  $-2.3\text{‰}$  ( $\delta^{18}\text{O}_p \sim 19.8\text{‰}$ ;  $\delta^{18}\text{O}_{dw} \sim -3.3/-4.0\text{‰}$ ). This is the lowest value of the complete sample set of this study and is indicative of a childhood spent in a warmer climate such as at the Italian coast, southern France or the Iberian Peninsula (Longinelli/Selmo 2003; Evans et al. 2012, 761; Fig. 12). The  $^{87}\text{Sr}/^{86}\text{Sr}$  value, which is close to seawater, could also indicate an origin from a coastal area.

The old male from the undestroyed poorly equipped grave 436 has a local  $^{87}\text{Sr}/^{86}\text{Sr}$  value but the  $\delta^{18}\text{O}$  value of  $-5.44\text{‰}$  ( $\delta^{18}\text{O}_p \sim 16.4\text{‰}$ ;  $\delta^{18}\text{O}_{dw} \sim -8.4/-9.1\text{‰}$ ) is decreased, pointing to an origin from an upland or more eastern area. The grave can only roughly be dated to the SD-phase 4–5.

Grave 425, which likely dates to the SD-phase 4, was also undestroyed and belongs to a juvenile male equipped with weapons and tools. The  $^{87}\text{Sr}/^{86}\text{Sr}$  value is lower than the local range and also the  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values are increased.

The individuals from graves 47 and 49 have  $^{87}\text{Sr}/^{86}\text{Sr}$  values which are slightly higher (grave 47) and slightly lower (grave 49) than the local range. Furthermore, both have  $\delta^{18}\text{O}$  values of around  $-5.0\text{‰}$ , which are slightly decreased. Both graves are of at least adult male individuals and because of the strong plundering of the graves they can only be dated to SD-phases 4 and 4–5 with uncertainty. The isotope values point rather to a non-local origin for at least a part of their childhood.

The remaining individuals from graves 37, 58, and 433 have isotope values which are indistinguishable from the local signatures of the Upper Rhine Valley. These are a young male from the grave 37 as well as an adult individual of unknown sex from grave 58. Both are strongly plundered and date only roughly in the SD-phase 4–5. Grave 433, with a hand-made pot of Thuringian provenance, belongs to a young female individual and dates to the SD-phase 4. The  $\delta^{18}\text{O}$  value is in the upper local range but a non-local region cannot be proven.

The multi-isotopic analysis of the eleven graves which date to the SD-phases 4 and 4–5 shows a large diversity of values. From eleven individuals, six are of non-local origin, while two are probably of non-local origin. Only three individuals have spent their childhood in the Upper Rhine Valley including a young female with a hand-made pottery vessel. It is difficult to evaluate if there was continuity between the founder community and the graves of the SD-phase 4 because only one tooth per individual was sampled. However, three individuals from the SD-phase 4 have radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values above the local range, similar to the founder graves which might indicate similar origin areas. In comparison with the preceding SD-phase 2–3, at the beginning of the 6<sup>th</sup> century there are more individuals which have at least spent parts of their childhood in the Upper Rhine Valley.

#### *Second third of the 6<sup>th</sup> century*

In the second third of the 6<sup>th</sup> century (SD-phase 5/5–6 = ca. 530–555/580), Eppstein has developed into a typical row-grave cemetery. However, hand-made vessels with parallels in the North Sea area are interpreted as indicators for newcomers from this region (Engels 2012, 200; 212–214). The vessels are only found in graves of children. A total of 15 from around 33 individuals from the SD-phases 5 and 5–6 have been analysed. These were eleven young adult to old adult individuals and four children. The graves are scattered over a wide area of the cemetery. An overview of the results of the strontium and oxygen isotopic analysis is presented in Fig. 8.3.

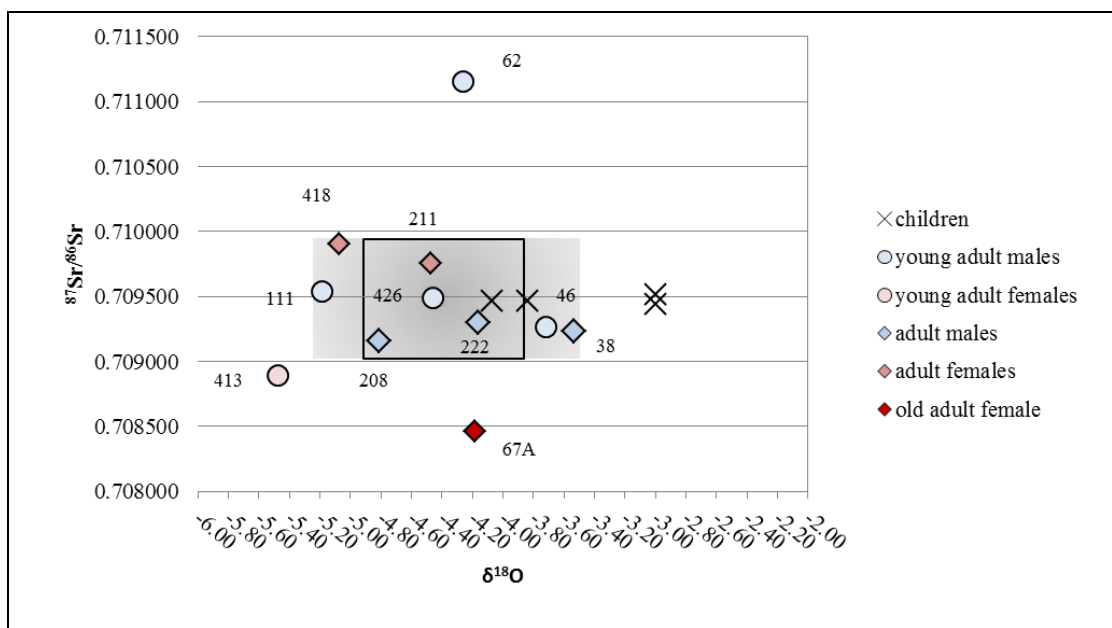


Fig. 8.3. Eppstein  $^{87}\text{Sr}/^{86}\text{Sr}$  vs.  $\delta^{18}\text{O}$  (SD-phases 5, 5–6).

Only three graves revealed isotope values which are clearly outside the local range. These are the graves 62, 67A and 413 which are all located in connection with older burials. Of these, the only  $^{87}\text{Sr}/^{86}\text{Sr}$  value which is more radiogenic than the local strontium signature is that from the juvenile male individual from the destroyed grave 62. Based on the few remaining objects, such as an arrowhead of Mediterranean-Byzantine influence, the grave is dated to the SD-phase 5–6. While the  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values are within the local range, the  $^{87}\text{Sr}/^{86}\text{Sr}$  value of 0.71115 points to an origin from regions with Buntsandstein, Keuper and basement rock. The grave is situated at the western fringe of the cemetery and based on the radiogenic value and the similar  $\delta^{18}\text{O}$  values to the graves 35 and 431 a connection to these burials is possible. Clearly outside the local range and therefore non-local is the older female individual from grave 67A, which was a secondary burial of grave 67C and probably dates to the SD-phase 5–6. The  $^{87}\text{Sr}/^{86}\text{Sr}$  value of 0.70846 is similar to those of graves 67C and 50. The increased  $\delta^{18}\text{O}$  value in comparison to the other graves might be explained at least partly by a breastfeeding effect because a canine tooth was analysed. Furthermore, the tooth was strongly abraded. However, a connection between the individuals from graves 50, 67C and 67A is probable. In addition, slightly less radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values have been measured in the tooth sample of the young adult female individual from the heavily plundered grave 413 which probably dates to the SD-phase 5. Furthermore, the  $\delta^{18}\text{O}$  value was decreased and the  $\delta^{13}\text{C}$  value is also rather at the lower limit of the range. A connection to the founder graves

67C and 50 as well as to the individual from grave 436 of the SD-phase 5–6 is possible. The remaining eight individuals from graves which can be dated to the SD-phases 5 or 5–6 have  $^{87}\text{Sr}/^{86}\text{Sr}$  values which are indistinguishable from the local signature. However, four of these have  $\delta^{18}\text{O}$  values which are in the upper or lower limit of the local range. Two of them, a male and a female from the destroyed graves 111 and 418, have slightly decreased  $\delta^{18}\text{O}$  values. Slightly increased  $\delta^{18}\text{O}$  values were seen in the two men from graves 38 and 46. While grave 38 was undestroyed but poorly equipped, grave 46 was strongly plundered but the remains of a bronze vessel indicate that the burial was of a wealthier person. Graves 208, 211, 426B, and 222 have isotopic values consistent with a childhood in the Upper Rhine Valley. The destroyed grave 211 belongs to a wealthier older person and dates to the SD-phase 5–6. From the SD-phase 5 four children also have been analysed. They show a very restricted  $^{87}\text{Sr}/^{86}\text{Sr}$  range between 0.70944 and 0.70969. The  $\delta^{18}\text{O}$  values for these individuals are increased and influenced by a breastfeeding effect because the M1/m1 was analysed.

For the SD-phase 5/5–6 an increase of local individuals can be detected. However, based on the results from graves 62, 413 and 67A, which are non-local and located in connection to burials of the preceding period, a continuity between the periods is present although the immigration from areas with more radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values clearly decreases. However, immigration specifically from the North Sea area is difficult to prove because the isotope values are similar to the Upper Rhine Valley.

#### *Second half of the 6<sup>th</sup> century*

In the second half of the 6<sup>th</sup> century (SD-phase 6/6–7 = ca. 555–580/600), the cemetery of Eppstein reached a remarkable population size in contrast to the preceding periods. At least 39 graves can be dated to this period; including those which cannot be assigned to this period with safety, the number increases to around 56 individuals. A total of 31 individuals have been analysed dating to the SD-phases 6 and 6–7. These samples include eight children, five older and six younger adults, as well as 12 individuals which are only determined as (at least) adult. The sex ratio is balanced (14male, 15 females, 2 undetermined). Most of the graves are situated in the northern part of the cemetery; only a few are scattered between the older graves in the southern part. There are no objects which indicate a foreign origin; the cemetery shows western-Frankish characteristics (Engels 2005a, 323; Engels 2012, 212–214).

Most graves are heavily plundered and destroyed in the same way as in the preceding periods. Similar to Dirmstein, the first burial mounds were constructed for burials of the highest social class. In contrast, there are no grave goods or grave constructions indicating a foreign origin for individuals at this time. However, the increase of burials in this period is still seen as the result of newcomers (Engels 2012, 196). An overview of the results of the strontium and oxygen isotopic analysis is presented in Fig. 8.4.

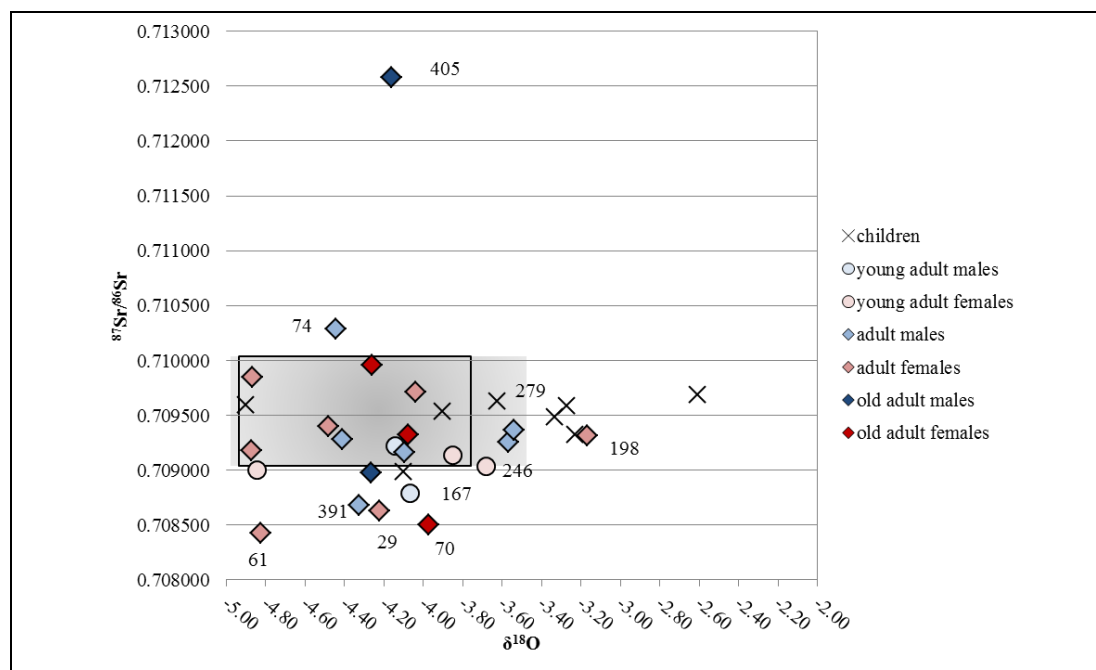


Fig. 8.4. Eppstein  $^{87}\text{Sr}/^{86}\text{Sr}$  vs.  $\delta^{18}\text{O}$  (SD-phases 6, 6–7).

A total of eight children were analysed (graves 25, 168, 182, 217, 224, 245, 422 and 435). They show a very restricted  $^{87}\text{Sr}/^{86}\text{Sr}$  range between 0.70932–0.70969. As expected, most of the  $\delta^{18}\text{O}$  values are increased as a result of breastfeeding effects. One child (grave 435) is of non-local origin because of a less radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  value below 0.70900. The  $\delta^{18}\text{O}$  value for this individual is also decreased in comparison to the other children. While the other children's graves are in the northern or northwestern area of the cemetery, this is the only grave which is located within the same burial area as graves from the SD-phase 4.

It is remarkable that there are only two graves of this period showing  $^{87}\text{Sr}/^{86}\text{Sr}$  values above the local range. The old male individual from grave 405 is located in the southwestern part of the cemetery. The burial is heavily destroyed but the find of a gold coin indicates that this was the grave of a person from a higher social class. The  $^{87}\text{Sr}/^{86}\text{Sr}$  value of 0.71258 is in the same range as the non-local male from grave 35 of



the SD-phase 4. The adult male from the destroyed grave 74 has a slightly elevated  $^{87}\text{Sr}/^{86}\text{Sr}$  of 0.71029; this grave dates to the SD-phase 6–7 and is located in the northern part of the cemetery. An additional grave of a non-local individual is situated south of the founder graves. The heavily destroyed grave 61 belongs to an adult, rather an older person, and has a less radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  value of 0.70843.

There is a group of five additional individuals (graves 29, 70, 71, 167, 391), with  $^{87}\text{Sr}/^{86}\text{Sr}$  values below 0.70900; their  $\delta^{18}\text{O}$  values are within the local range but they are all above  $-4.5\%$ . Four of these graves are located in the northwestern part of the cemetery; only one is situated in a more southern area, directly north of the graves from the SD-phase 2–3. This group represents a small group of new immigrants from an area with a similar  $\delta^{18}\text{O}$  to the Upper Rhine Valley but lower  $^{87}\text{Sr}/^{86}\text{Sr}$  values.

There are four individuals with local  $^{87}\text{Sr}/^{86}\text{Sr}$  but increased  $\delta^{18}\text{O}$  values (graves 197, 246, 279, 198). However, only the individual from grave 198 is clearly outside the local range and points to an origin in a warmer climate than the Upper Rhine Valley. The young adult female individual from grave 4C has local  $\delta^{18}\text{O}$  values but  $^{87}\text{Sr}/^{86}\text{Sr}$  values at the lower limit of the local range.

The remaining individuals (graves 3, 30, 39, 55, 162, 188, 226, 421, 233, 228) have isotope values which are consistent with a childhood spent in the Upper Rhine Valley, including the young adult individual of grave 167 with the burial mound assigned to quality group B2.

The multi-isotopic analysis of the graves from the second half of the 6<sup>th</sup> century have shown that immigrations from regions east of the Rhine and from upland areas with older geology were almost absent. This is indicated by the lack of individuals with decreased  $\delta^{18}\text{O}$  values. Furthermore, there are only 2 out of 31 with  $^{87}\text{Sr}/^{86}\text{Sr}$  values above the local range. However, it has been detected that new immigrations from more western areas took place, which is shown by  $^{87}\text{Sr}/^{86}\text{Sr}$  values below the local range and slightly increased  $\delta^{18}\text{O}$  values. These insights are in accordance with the archaeological evidence which shows mainly western-Frankish influences (Engels 2012, 214). Furthermore, the rich “elite” graves revealed mainly local isotopic values.

## 8.2 Bockenheim

The archaeological investigation of the early medieval cemetery of Bockenheim is not finished yet. However, this burial place is one of the few burial places in the Palatinate and Rhine Hesse region besides Eppstein which yielded a larger number of graves from the late 5<sup>th</sup> and early 6<sup>th</sup> centuries. The preliminary information is detailed enough to make it comparable to the two other cemeteries under study. An overview of the results of the strontium and oxygen isotopic analysis is presented in Fig. 8.5.

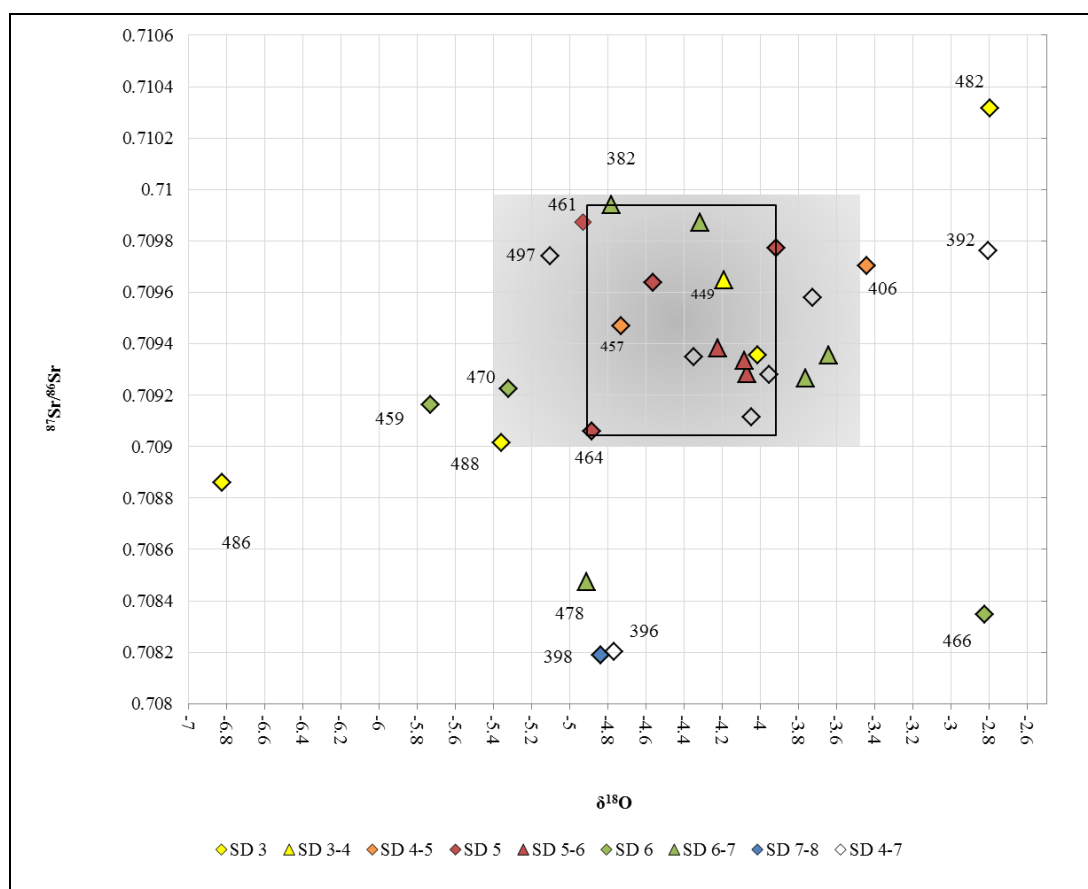


Fig. 8.5. Bockenheim  $^{87}\text{Sr}/^{86}\text{Sr}$  vs.  $\delta^{18}\text{O}$  by SD-phase.

The earliest graves of the Bockenheim cemetery date to the late 5<sup>th</sup> and the early 6<sup>th</sup> century (SD-phase 2–3 = ca. 460–480/510) but the occupation of the cemetery is considered to have more likely been during the SD-phase 3 (Riemer pers. comm.). The cemetery is not completely excavated and additional early graves are considered likely to arise during further work at the site (Riemer pers. comm.). A total of four founder graves were analysed. The partly destroyed grave 391 dates to the late 5<sup>th</sup> century and belongs to an older woman. The only grave offering was a glass vessel. All isotope systems show local values for this woman and are therefore

consistent with a childhood in the Upper Rhine Valley. The most radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  signature of the complete sample set from Bockenheim, with a  $^{87}\text{Sr}/^{86}\text{Sr}$  value of 0.71032, comes from the adult female individual from grave 482; this grave dates to the turn of the 5<sup>th</sup> to the 6<sup>th</sup> century (SD-phase 3) and was probably not plundered. The burial was richly equipped with jewellery, tools, silver coins, a clover leaf jug, food offerings, and a glass vessel, as well as a brooch which is typical for Gothic and Frankish areas (Bernhard 1997, 40; Bernhard 1997, 44, Fig. 19). The measured  $^{87}\text{Sr}/^{86}\text{Sr}$  value is identical to those of graves 275 and 83 from Eppstein. However, the  $\delta^{18}\text{O}$  value of  $-2.8\text{‰}$  ( $\delta^{18}\text{O}_p \sim 19.2\text{‰}$ ;  $\delta^{18}\text{O}_{dw} \sim -4.1/-4.8\text{‰}$ ) is highly enriched and a common origin is rather unlikely. The  $\delta^{13}\text{C}$  signature of  $-11.9\text{‰}$  is slightly elevated in comparison to most of the samples but still in the normal range. The enriched  $\delta^{18}\text{O}$  value indicates that the woman from grave 482 spent her childhood in a region with a warmer climate. The converted and corrected  $\delta^{18}\text{O}_{dw}$  value of  $-4.8\text{‰}$  is consistent with parts of the Iberian Peninsula, southern France and the Mediterranean area (Longinelli/Selmo 2003; Evans et al. 2012, 761; Fig.12). A further early grave which dates to the second half of the 5<sup>th</sup> century is burial 488 of a young woman. Among the few remaining objects was a large bronze Gothic bow brooch (type Mainz-Bretzenheim after Kühn) which is distributed in the Rhineland and northern France (Bernhard 1997, 40). While the  $^{87}\text{Sr}/^{86}\text{Sr}$  value for this woman is at the lower limit of the local signature, the  $\delta^{18}\text{O}$  value of  $-5.4\text{‰}$  ( $\delta^{18}\text{O}_p \sim 16.5\text{‰}$ ;  $\delta^{18}\text{O}_{dw} \sim -8.3/-9\text{‰}$ ) is decreased and shows that she spent her childhood in a different area than the Upper Rhine Valley. Grave 486 of an older woman dates around 500 or the first decade of the 6<sup>th</sup> century and was equipped with a set of four brooches, a silver arm ring and other grave offerings (Bernhard 1997, 50; Riemer 2008, 153–154, Fig. 3). The  $^{87}\text{Sr}/^{86}\text{Sr}$  value of 0.70886 is lower than the local range and the  $\delta^{18}\text{O}$  value of  $-6.8\text{‰}$  ( $\delta^{18}\text{O}_p \sim 15.0\text{‰}$ ;  $\delta^{18}\text{O}_{dw} \sim -10.7/-11.4\text{‰}$ ) is the lowest of all measured samples from this study. The decreased  $\delta^{18}\text{O}$  signature points to a colder and higher region than the Upper Rhine Valley. This combination of  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\delta^{18}\text{O}$  values has, for example, been measured in Bronze and Iron Age communities of Southwest Germany (Oelze et al. 2012a; Oelze et al. 2012b). Similar to Eppstein, the analysed founder graves from Bockenheim show a large variability in their  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\delta^{18}\text{O}$  values. Three of the four female individuals are of non-local origin and spent their childhood in different regions. Only the older woman from grave 391 appears to have spent her childhood in the Upper Rhine Valley. The results are clearer than for the older woman from grave

280 at Eppstein. Connections between the two cemeteries are difficult to obtain because only one tooth per individual was sampled. However, a tentative connection could be indicated by the similar  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\delta^{18}\text{O}$  values of grave 488 from Bockenheim and burials 67C and 50 from Eppstein.

Only one individual was sampled which can be dated to the beginning of the 6<sup>th</sup> century. Two further graves can only be dated roughly to the SD-phases 4–5. One burial of a local individual was the female child from grave 449 which already dates to the first half of the 6<sup>th</sup> century (SD-phase 3–4) and was equipped with two small eagle brooches, two whorls, several beads and a ceramic beaker (Bernhard 1997, 40). The young male from grave 457 also shows a local isotope signature. This is not the case for the older female individual from grave 406. While the  $^{87}\text{Sr}/^{86}\text{Sr}$  value shows a local signature, the  $\delta^{18}\text{O}$  value of 3.4‰ ( $\delta^{18}\text{O}_p \sim 18.6\text{‰}$ ;  $\delta^{18}\text{O}_{dw} \sim -5.1/-5.8\text{‰}$ ) is increased, indicating rather a southwestern origin. However, the sampled tooth from the woman was strongly abraded and it may be the case that the sample is elevated as a result of the biased sampling technique.

Six samples have been analysed which date to the SD-phases 5 or 5–6 (graves 454, 424, 464, 22, 423, 395). These are two children, two adult male individuals, one older female and a younger adult male individual. All individuals have  $^{87}\text{Sr}/^{86}\text{Sr}$  values that are consistent with a childhood spent in the Upper Rhine Valley. This is also the case for the  $\delta^{18}\text{O}$  values. Only one individual, the older female from grave 424, has an increased  $\delta^{13}\text{C}$  value of  $-10.4\text{‰}$  which indicates a slight  $\text{C}_4$  component in the diet. For Bockenheim, it is also assumed that individuals from Middle Germany are present because of the presence of hand-made pottery from this region, for example, in grave 423 of a local child (Riemer pers. comm.). A Thuringian hand-made pot was also found in grave 454 which was identified as local. It is striking that the individuals from Bockenheim do not show more radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  as in Eppstein or Dirmstein.

A total of nine individuals have been analysed that date to the second half of the 6<sup>th</sup> century. One of these individuals dates as late as the beginning of the 7<sup>th</sup> century (SD-phases 6, 6–7, 7–8). In total, there is a younger female and male individual, two older females and one old man, as well as two adult males and one adult woman. One adult individual is of unknown sex. In contrast to the individuals of the first half and the middle of the 6<sup>th</sup> century, the number of outliers increases in this later period. There are five individuals with non-local values. Three of them have

$^{87}\text{Sr}/^{86}\text{Sr}$  values that are lower than the local range. These are an adult male (grave 466), an adult woman (grave 478) and a senile male from the grave 398. While the  $\delta^{18}\text{O}$  values of individuals from the graves 478 and 398 are indistinguishable from the local value, the male from grave 466 has an increased  $\delta^{18}\text{O}$  value of  $-2.8\text{‰}$  ( $\delta^{18}\text{O}_p \sim 19.2\text{‰}$ ;  $\delta^{18}\text{O}_{dw} \sim -4.1/-4.8\text{‰}$ ). The two individuals from graves 459 and 470 revealed decreased  $\delta^{18}\text{O}$  values between  $-5.7\text{‰}$  and  $-5.3\text{‰}$  ( $\delta^{18}\text{O}_p \sim 16.1$  and  $16.6\text{‰}$ ;  $\delta^{18}\text{O}_{dw} \sim -8.9/-9.6\text{‰}$  and  $-8.2/-8.9\text{‰}$ ) while their  $^{87}\text{Sr}/^{86}\text{Sr}$  values showed a signal also typical for the Upper Rhine Valley. These individuals are a young adult woman and older male. The remaining samples (graves 386, 382, 492, 421) have values which are consistent with a childhood spent in the Upper Rhine Valley.

Eight individuals were sampled which can only be dated to the 6<sup>th</sup> century without specifying which period (Riemer pers. comm.). These are four children and four female individuals; the latter comprise one young adult, one adult, and two adults of advanced age. One of the children, from grave 396, has a non-local  $^{87}\text{Sr}/^{86}\text{Sr}$  value and clusters with the individuals from graves 478 and 398, indicating a common origin. Except for a senile female individual from grave 392 with increased  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values, the remaining three children and three females have isotope values which are typical for the Upper Rhine Valley.

The multi-isotopic analysis has shown that the founder graves of the Bockenheimer cemetery are also of diverse origins including a local component. It is striking that there are no individuals with  $^{87}\text{Sr}/^{86}\text{Sr}$  values above 0.71050 which is in contrast to the cemeteries Eppstein and Dirmstein.

### 8.3 Dirmstein

The first aim of the investigation of the early medieval cemetery of Dirmstein was to detect locals and non-locals by means of strontium, oxygen and carbon isotopes. The results have shown that the 25 analysed individuals exhibit a large variability of isotopic values indicating a large number of non-local individuals (see Fig. 8.6).

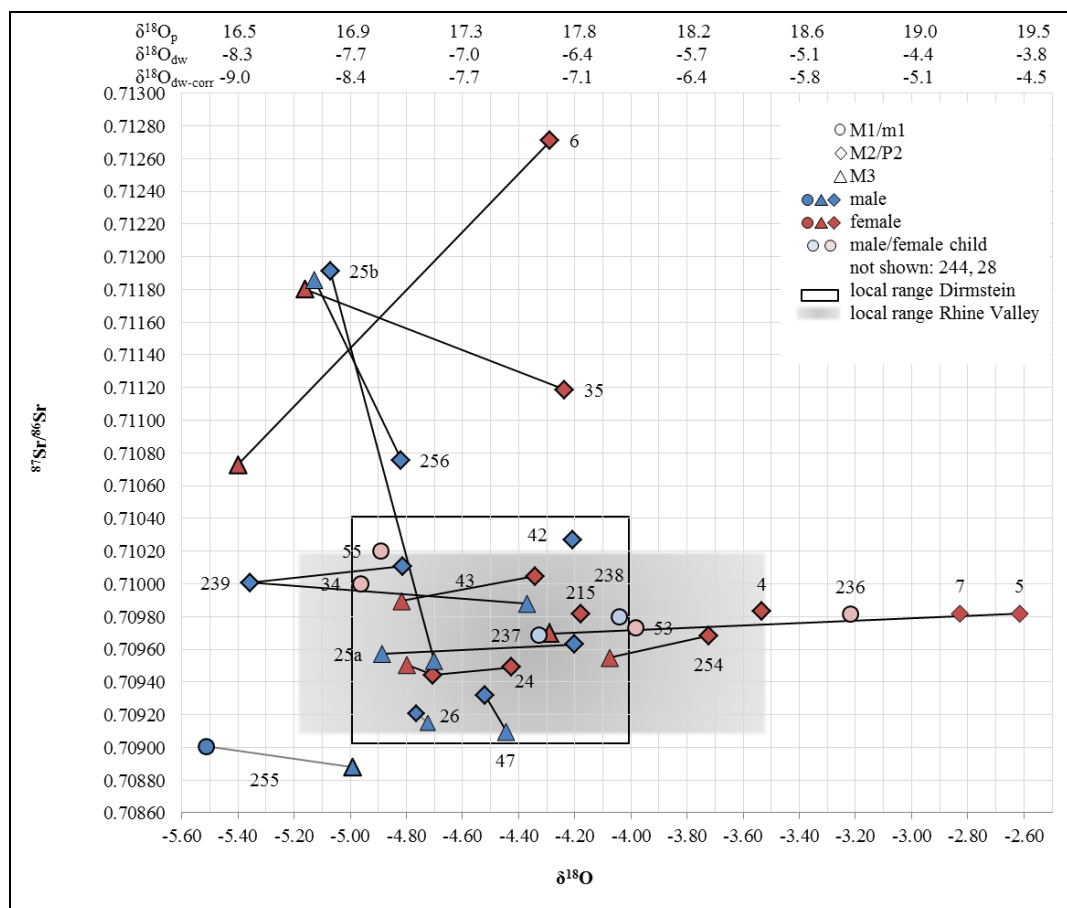


Fig. 8.6. Dirmstein  $^{87}\text{Sr}/^{86}\text{Sr}$  vs.  $\delta^{18}\text{O}$ .

A total of 6 out of 25 individuals revealed  $^{87}\text{Sr}/^{86}\text{Sr}$  values above 0.71400 (graves 6, 25b, 28, 35, 244, and 256). Two of these individuals, the mature man from grave 244 in the western part of the cemetery and the undeterminable adult individual from the south-north-orientated grave 28, have the most striking  $^{87}\text{Sr}/^{86}\text{Sr}$  values. The man from the undestroyed grave 244 was relatively simply equipped with a belt-buckle, spatha, knife/short sax, tweezers, awl and a flint. None of these objects point to a non-local origin for this person. The strontium isotopic analysis revealed that both sampled teeth have highly radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values of 0.72938 (M2) and 0.71653 (M3). Comparable high values are only known from upland regions with outcropping crystalline basement rock, such as in Scandinavia, Scotland, the Alps, the Vosges, the Bavarian Forest, northern Switzerland or the Massif Central (Åberg et al. 1998; Sjögren/Price 2013; Sjögren et al. 2009; Montgomery et al. 2006b; Voerkelius et al. 2010; Hoogewerff et al. 2001; Müller et al. 2003; Kelly 2007; Grupe et al. 2011). While the  $\delta^{13}\text{C}$  values of both teeth are within the normal range for  $\text{C}_3$ -based terrestrial diet, the  $\delta^{18}\text{O}$  values ( $-5.8\text{‰}$ ,  $-5.8\text{‰}$ ) are the lowest of the complete sample set. When transforming the  $\delta^{18}\text{O}$  values into meteoric water values as described above

(see 7.2) ( $\delta^{18}\text{O}_p \sim 16.0\text{‰}$ ;  $\delta^{18}\text{O}_{dw} \sim -9.0/-9.8\text{‰}$ ) this points to a childhood spent in an upland area such as the Alps or more eastern areas. Comparable low  $\delta^{18}\text{O}$  values were measured in human tooth enamel from the Iron Age Magdalenenberg site in Southwest Germany (Oelze et al. 2012a).  $\delta^{18}\text{O}_{\text{cVPDB}}$  values of around  $-5.0$  to  $-6.0\text{‰}$  were also measured from human tooth enamel of individuals from the 15<sup>th</sup> to 18<sup>th</sup> century St-Benedict cemetery in Prague (Salesse et al. 2013). The individual from grave 28 shows similar  $^{87}\text{Sr}/^{86}\text{Sr}$  values (above 0.72000) as well as decreased  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values. The  $\delta^{13}\text{C}$  value of the canine tooth is, at  $-15.1\text{‰}$ , the most decreased of the complete data set. As the analysed teeth were a canine and premolar, the slightly higher  $\delta^{18}\text{O}$  values in comparison to individual 244 as well as the decreased  $\delta^{13}\text{C}$  could indicate a breastfeeding effect. The grave is heavily destroyed and plundered, and only the remains of a comb and a small bronze buckle which date the grave to the SD-phase 5–6 are present (Leithäuser 2011, 234). However, the most important feature is the south-north orientation of the grave and its location within the group of burials which were interpreted as foreign, originating from a North Sea or Anglo-Saxon area. The origin of this person from these regions can be excluded because the measured isotopic  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\delta^{18}\text{O}$  values are not typical for the North Sea area (von Carnap-Bornheim et al. 2007; Gillmaier et al. 2009; Evans et al. 2010; Smits et al. 2010; McManus et al. 2010; Vohberger 2010; Grupe et al. 2011; Degryse et al. 2012; Price et al. 2013).

The second group of individuals with non-local, more radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values above 0.71050 is comprised of four individuals (6, 25b, 35, 256). The burial of the female adult individual from grave 6, which is located in the western area of the cemetery, is almost completely destroyed. Only few remains are present such as a fragment of a glass vessel, an iron ring and comb fragments. The grave was dated to the SD-phase 5 because of its location between other graves of this period but a date in the SD-phase 6 is also possible. The M2 of this woman has a radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  value of 0.71271 and a relatively low  $\delta^{13}\text{C}$  value of  $-14.9\text{‰}$ . The  $\delta^{18}\text{O}$  value is consistent with the local oxygen signature of the Upper Rhine Valley. The M3 has a less radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  value of 0.71073. While the  $\delta^{13}\text{C}$  value corresponds to the values of most of the other individuals, the  $\delta^{18}\text{O}$  value is slightly decreased. Based on these results it can be stated that this person changed her subsistence resources during childhood and youth which is probably the result of a residence change. While the values of the M2 have no similarities to other individuals, the M3 shares the same

$^{87}\text{Sr}/^{86}\text{Sr}$  value and almost exactly the same  $\delta^{13}\text{C}$  value with the adult male individual from the destroyed grave 256 in the eastern part of the cemetery. This may indicate that the woman from grave 6 moved to the residence area of the male individual during her youth. The destroyed and plundered grave 256 of an adult male individual can be dated to the SD-phase 6 based on the few remaining objects such as buckles, a knife, scissors, pottery, flint, arrowhead, and a glass vessel. A further close connection is detectable between the person from grave 256 and two other graves; the M3 has almost the same  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\delta^{18}\text{O}$  values as the M3 of the female from grave 35 as well as the P2 of the male from grave 25b. This implies that the persons from graves 256 and 35 moved during their youth to the place where the male from grave 25b spent his childhood. The grave of the female adult individual from grave 35 is situated in the southern part of the cemetery. The burial is heavily destroyed but the remaining grave goods such as a wheel-made ceramic vessel date the grave to the late SD-phase 6. The M3 of the individual from grave 25b shows  $^{87}\text{Sr}/^{86}\text{Sr}$ ,  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values which are common for the Upper Rhine Valley. The non-local signal for the P2 and the local signal for the M3 indicate that this person moved to the Upper Rhine Valley during his youth, maybe together or from the same area than the individuals from the graves 256, 35 and 6. However, based on the results of the M2/P2s of these individuals, they spent their childhood in different areas. The origin of this group is difficult to evaluate because  $^{87}\text{Sr}/^{86}\text{Sr}$  values between 0.71070 and 0.71270 are typical for several geological areas. However, in combination with the slightly decreased  $\delta^{18}\text{O}$  values of most of the teeth, several regions can be excluded such as the areas of cover sand and glacial moraines of the North German Plain, Denmark, the coastal areas of the Netherlands, Belgium and northern France, and Britain, which means the North Sea area (Smits et al. 2010; Vohberger 2011; Brettell et al. 2012a; McManus et al. 2013). Therefore, an origin from a Palaeozoic or Mesozoic metamorphic rock upland areas is more probable. Similar  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\delta^{18}\text{O}$  values in human tooth enamel from different time periods were measured east of the Rhine in the Wetterau and Odenwald region but also in more southern areas near Lake Constance or in the Palaeozoic uplands in the south of Northeastern Germany (Bentley/Knipper 2005; Haak et al. 2008; Nehlich et al. 2009; de Jong et al. 2010; Haak et al. 2010; Oelze et al. 2012b; Oelze et al. 2012a; Knipper et al. 2012a; Knipper et al. 2014).

Grave 25b of the male adult person was circumscribed by a circular ditch and a burial mound. The grave was heavily destroyed but the remaining grave goods such



as a harness, a coin, and weapons indicate that this was a burial of the higher social class. The rich graves with burial mounds are generally interpreted as the leaders of the community. Within the second burial mound at the cemetery Dirmstein lay the undestroyed grave 254 of the SD-phase 6 (ca. 555–580) which belongs to a juvenile female individual. This is the most richly furnished burial of the cemetery and one of the richest female graves of the Palatinate region (Bernhard 1997, 43). The young woman was buried in a large burial pit which was surrounded by a circular ditch and covered by a mound. The high social status of this person is also reflected by the numerous precious grave goods and dress accessories which were partly produced in non-local workshops but also obtained from local sources. Furthermore, the grave goods also included objects which were interpreted as symbols of property and responsibility for house and yard, as well as textile production, signalling that this was the burial of a person from the uppermost social class (Leithäuser 2011; Koch 2012). The grave also contained three ceramic vessels. One of these was hand-made which shows, according to Leithäuser, similarities to vessels of the 5<sup>th</sup> century from cemeteries in Northwest Germany as well as to pottery from Anglo-Saxon cemeteries of the 6<sup>th</sup> century (Leithäuser 2011, 167–169). Some features can also be found on pottery from the cemetery of Wenigumstadt 40 km east of Dirmstein which were also interpreted as evidence for immigrants from northern Germany, especially Holstein and the Anglo-Saxon area. These “foreign” hand-made vessels, as well as the south-north orientation of some graves, were the main reasons for the assumption that the eastern part of the cemetery was founded by an immigrated family, possibly from the Anglo-Saxon or North Sea area. However, the Anglo-Saxon origin of these vessels such as in Wenigumstadt is not generally accepted. Some researchers view the vessels rather as a derivation of pottery from the “Elbe-Germanic”, Thuringian-Langobardian cultural context (Quast 2005, 438). A similar vessel was, for example, found in a rich female grave from a cemetery in Beuchte, north of the Harz Mountains near Goslar, which dates to the second quarter and the middle of the 6<sup>th</sup> century (Ludowici 2005, 87–90, Taf. 87, 1). Both sampled teeth from the young woman of the grave 254 revealed  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\delta^{18}\text{O}$  values which are consistent with the local  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\delta^{18}\text{O}$  ranges of the Upper Rhine Valley. This indicates that this person from the uppermost social class spent their childhood and youth in the Upper Rhine Valley. However, it needs to be mentioned that the  $\delta^{18}\text{O}$  values which are typical for the Upper Rhine Valley, especially the lower range between  $-4.5\text{‰}$  and  $-4.0\text{‰}$

(correspondingly  $\delta^{18}\text{O}_p \sim 17.5\text{‰}$  to  $18.0\text{‰}$ ;  $\delta^{18}\text{O}_{dw} \sim -7.0\text{‰}/-7.5\text{‰}$ ), are also common for more western areas including the North Sea area. This is also the case for the local strontium signature of the Upper Rhine Valley.

Three female individuals from graves 4, 5 and 7, which are arranged in a row in the western part of the cemetery, yielded increased  $\delta^{18}\text{O}$  values above around  $-3.5\text{‰}$ . Two of them are young adults while the third is only determined as adult. The graves are heavily destroyed and plundered and none of the few remaining objects point to a foreign origin. They all show local  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\delta^{13}\text{C}$  values which are all almost identical. This implies that the three women had a common (restricted) dietary intake during childhood. The elevated  $\delta^{18}\text{O}$  values point to an  $^{18}\text{O}$ -enriched water source during childhood which may be the result of these individuals originating from a more southern area. However, the M3 from the individual of grave 5 was also analysed, which revealed an almost identical  $^{87}\text{Sr}/^{86}\text{Sr}$  to the M2 but the  $\delta^{18}\text{O}$  value of the M3 was more than  $1.5\text{‰}$  decreased in comparison to the M2 and yielded a local value. The almost identical  $^{87}\text{Sr}/^{86}\text{Sr}$  value of the M2 and M3 speaks against a residence change during childhood. An alternative explanation for the  $^{18}\text{O}$ -enriched water source may be a certain water source or special food.

An additional individual that is clearly non-local to the Upper Rhine Valley is the older male individual from the mainly undestroyed grave 255, located in the eastern part of the cemetery. He was equipped with a buckle, weapons, tools, and a coin. The  $^{87}\text{Sr}/^{86}\text{Sr}$  values of the measured M1 and M3 are less radiogenic than the local range and the decreased  $\delta^{18}\text{O}$  values clearly show that he spent his childhood and youth in a different area than the Upper Rhine Valley and the North Sea area.

Most of the remaining adult individuals have isotopic signatures that are indistinguishable from the local signature of the Upper Rhine Valley and most probably spent their childhood and youth in the region (graves 24, 25a, 215, 43, 47, 26). They are distributed throughout the whole cemetery and show no signs of a foreign origin. These are the individual from grave 25a which contains no grave goods, the adult female individual from grave 24 which can be dated to the SD-phase 5 based on the few remaining objects, and the older adult female from the destroyed grave 215 dating to the SD-phase 6. In addition, grave 43 of a young adult female in the southern part of the cemetery which dates to the SD-phase 6 also has isotope values that are consistent with a childhood spent in the Upper Rhine Valley. This is also the case for the individuals from graves 26 and 47. However, it is remarkable that

both have slightly less radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values than all other local individuals. The male adult individual from the destroyed grave 26 was located in the western part of the cemetery and the remaining grave goods such as arrowheads can be dated to the SD-phase 5. The sampled teeth show only minor differences, indicating no residential change during childhood and youth. Grave 47 belongs to a relatively poorly equipped adult male individual that dates to the SD-phase 5. The sampled teeth show also only minor differences between each other, but the  $^{87}\text{Sr}/^{86}\text{Sr}$  value of the M3 is rather in the lower limit of the local range. Even if the values of these two individuals are indistinguishable from the local range, it has to be mentioned that these values are also typical for coastal areas and have been measured in tooth enamel of local individuals from Neolithic and Early Medieval period from the Netherlands (Smits et al. 2010; McManus et al. 2013).

There are two remaining adult individuals that merit further discussion. Only one tooth, probably M1, was analysed from the adult male individual of the destroyed grave 42 of the SD-phase 6 in the southern part of the cemetery. While the  $\delta^{18}\text{O}$  value shows a local signal, the  $^{87}\text{Sr}/^{86}\text{Sr}$  value is in the upper limit of the local strontium signature for Dirmstein (but above the range for Eppstein and Bockenheim) and the  $\delta^{13}\text{C}$  value is rather in the upper range. In this case it is questionable whether this individual obtained food and drinking water from the Upper Rhine Valley.

A further grave with somewhat outlying values is that of the at least adult (not juvenile/adult I as written in the publication by Leithäuser) male person from grave 239 in the eastern part of the cemetery. The grave was overlapped by another grave but the grave goods, which are comprised of a hand-made pottery vessel of Anglo-Saxon tradition, spatha, sax, buckle, comb, knife, scissors, glass vessel, and a firesteel, were probably complete and date the grave to the SD-phase 5. A total of three teeth were analysed which have  $^{87}\text{Sr}/^{86}\text{Sr}$  values around 0.71000 and are therefore in the upper local range for Dirmstein. While the M3 has also local  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values, the isotope ratios of the P2 and M2 are more variable which is curious as they mineralise at the same time. The teeth of this individual were in a very poor state of preservation and strongly abraded. It is most likely that the values differ as a result of the sampling technique. The  $\delta^{18}\text{O}$  value of the M2 is outside the local range while that from the P2 is in the upper range. It is likely that this individual obtained food and drinking water from another area than the Upper Rhine Valley during the

mineralisation of the P2 and M2 and then moved to the Upper Rhine Valley as indicated by the local isotope values of the M3.

The analysed M1/m1s of six non-adult individuals have  $^{87}\text{Sr}/^{86}\text{Sr}$  values between 0.70969 and 0.71020. All of them probably obtained food and drinking sources from the direct area of Dirmstein. Four of them, the children from graves 53, 236, 237 and 238, also have elevated  $^{87}\text{Sr}/^{86}\text{Sr}$  and decreased  $\delta^{13}\text{C}$  signatures as expected as a result of a breastfeeding effect. Graves 237 and 238 are located in the eastern part of the cemetery and grave 237 also contains a fragment of a hand-made pottery vessel of Saxon or Anglo-Saxon influence (Leithäuser 2011, 165). The isotopic values of the two children from graves 34 and 55 are striking. They have the most radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values of all the children, their  $\delta^{18}\text{O}$  isotope values are depleted in comparison to the local range and their  $\delta^{13}\text{C}$  isotope values are not decreased but in the range of adult local individuals. The most likely explanation is that these children did not spend the entire time of tissue formation of their M1 in the Upper Rhine Valley or that their mother(s) were of non-local origin, from a region with more radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values.

### *Conclusion*

Based on the results of the isotopic analysis, the aim was to test if the cemetery was used by two spatially-separated burial communities with a foreign group in the eastern part of the cemetery and a local group in the western part. For the immigrated group, an origin from the North Sea area was supposed, based on hand-made pottery of Anglo-Saxon tradition and south-north orientated graves (Leithäuser 2011, 222–227). The isotopic analysis has shown that around half of the sampled individuals are of non-local origin. They are distributed throughout the whole cemetery, encompassing all sexes and age groups, as well as social groups (see Fig. 8.7). Most of the non-local individuals had more radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values than the local signature (above 0.71050) or decreased  $\delta^{18}\text{O}$  values in comparison to the estimated local  $\delta^{18}\text{O}$  range of the Upper Rhine Valley or a combination of both. These results exclude an origin from the North Sea area for these individuals because these values are not common. This applies for ten individuals who are identified as non-local. However, it has to be mentioned that large parts of the North Sea area show similar  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\delta^{18}\text{O}$  values to the Upper Rhine Valley. Typical  $^{87}\text{Sr}/^{86}\text{Sr}$  values for the North Sea area are between 0.70900 and 0.71000 and  $\delta^{18}\text{O}_{\text{dw}}$  values are

between  $-7.0\text{‰}$  and  $-7.5\text{‰}$  which corresponds to the  $\delta^{18}\text{O}$  range between  $-4.0$  and  $-4.5\text{‰}$  at Dirmstein. Therefore, it cannot be excluded that the young female from grave 254 with the hand-made pottery of supposed Anglo-Saxon tradition or the male from the south-north orientated grave 47 originated from this area. At this point, the methodology of strontium isotope analysis has been reached. However, it has also to be mentioned that the interpretation of the Anglo-Saxon origin of the supposed hand-made vessels is not generally accepted and similar vessels are known from other regions “Elbe-Germanic”, Thuringian-Langobardian cultural context as well as from Southwest Germany. However, it can be stated that the presence of an immigrated group with origins in the North Sea area cannot be proven by means of the isotope analysis. Furthermore, it was detected that non-local individuals were not only concentrated in the eastern, supposed foreign, area of the cemetery but are distributed over the complete cemetery. Hand-made pottery and south-north orientated graves were connected to individuals of local as well as of non-local origin. Hand-made pottery was also found in graves of children with local origins. This does not contradict the assumption that hand-made pottery indicates the presence of foreign groups but underpins that the objects were chosen by the relatives of the interred individuals and rather represents the origin of the family and relatives of the deceased. Based on the more radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values and decreased  $\delta^{18}\text{O}$  values for most of the non-locals, an origin from a more eastern (or southern) area with older geology than the Upper Rhine Valley is assumed. This includes regions in Middle Germany as well as Southwest Germany and also the adjacent Odenwald or Wetterau region. Furthermore, based on the observation that several non-local individuals had similar isotopic values, including adult males and females (graves 6, 25b, 35, 256) as well as children (graves 34, 55), this tentatively indicates that there was an immigration of a group of people originating from the same area. This could indeed reflect administrated settlement processes of non-local groups in the Upper Rhine Valley in the name of the Merovingian kings, in order to consolidate power in the expansion areas east and west of the Rhine or as land grants awarded for military services. This assumption is supported by the fact that the male from grave 25b, considered to be of the uppermost social class, moved to the Upper Rhine Valley during his youth probably together with his family as reflected by the similar isotope values and, speculatively, with followers from other regions as reflected by the non-local but different isotope values. However, the single non-locals such as the male from grave

255 could indeed also reflect individual mobility. In the case of the female individuals with increased  $\delta^{18}\text{O}$  values but local  $^{87}\text{Sr}/^{86}\text{Sr}$  values it is likely that they are of non-local, more southern origins, but it cannot be excluded that the increased  $\delta^{18}\text{O}$  value is the result of a special diet.

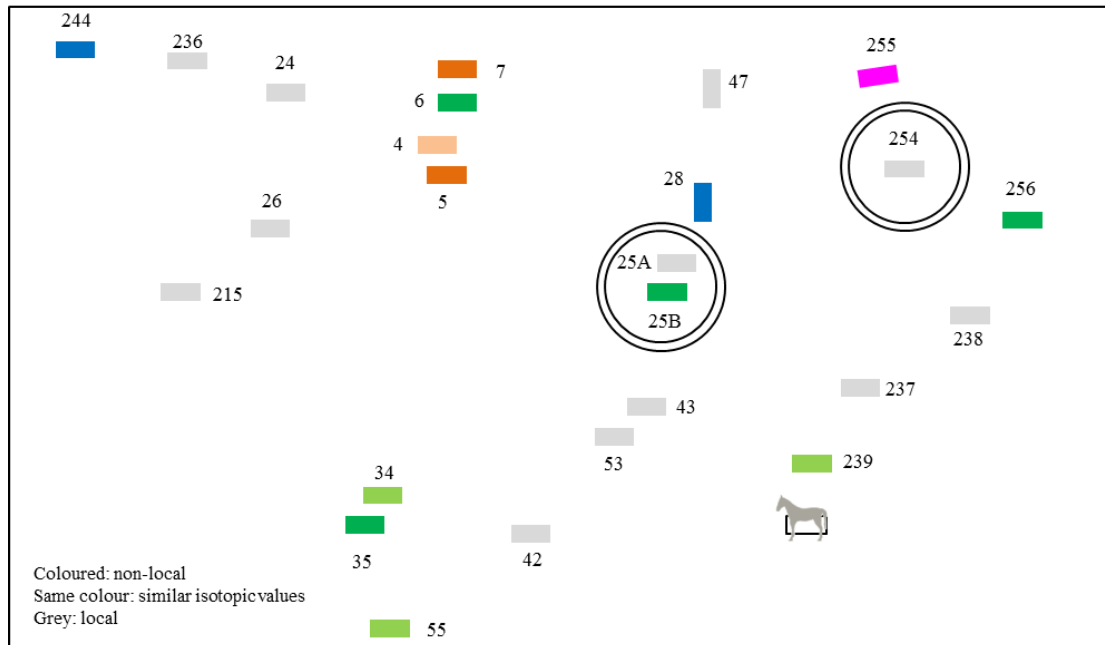


Fig. 8.7. Dirmstein overview locals and non-locals.

## 9 Conclusions

### 9.1 Diversity and mobility in the early medieval Upper Rhine Valley

#### *The founder graves*

Some of the earliest graves in Eppstein were created at a time when the Upper Rhine Valley was not yet under the reign of the Merovingians (SD-phase 2; ca. 460–480) (Engels 2012, 198). The second half of the 5<sup>th</sup> century was an unstable time; the Western Roman Empire ceased and was gradually replaced by several independent “Romano-barbarian kingdoms”. Although the few written sources reporting about the Upper Rhine area are meagre and debated, extensive statements have been made concerning the settlement of this region in the second half of the 5<sup>th</sup> century after the Roman military influence had lapsed (see chapter 1.2.1). Some researchers suppose an Alemannic settlement or at least a military influence zone (Ewig 1979, 278–279; Grünewald 1996, 160). Other researchers exclude an extensive Alemannic settlement and assume that the Alemannic period described in the written sources was only within a short time frame around 500. Instead, it is hypothesised that Rhenish Franks together with former federate soldiers of “Germanic” origin and remaining late Roman provincial communities settled in the western Upper Rhine Valley (Staab 1975, 12; Staab 1996, 238; Wieczorek 1996, 242; Knöchlein 2003, 137–138). Archaeological investigations have shown that Roman structures in the rural areas were still intact until the second half of the 5<sup>th</sup> century, or even until the end of the 5<sup>th</sup> century (Bernhard 2008a, 105); at a time when the first early medieval cemeteries had already been founded. For urban centres such as Mainz and Worms, proof for a settlement in the second half of the 5<sup>th</sup> century is still difficult (Knöchlein 2011, 276–282; Grünewald/Wieczorek 2012, 12–15). In contrast, Speyer was continuously settled between late Roman and early medieval times based on excavated settlement structures as well as graves (Bernhard 2007, 118–119). However, in all three centres the presence of individuals of “Germanic” origin, as shown by single finds, names on grave stones or ceramics from settlements, is assumed for the 5<sup>th</sup> century. This is also the case for the military fortifications whose military period ends in the middle of the 5<sup>th</sup> century, whereafter a civil settlement is supposed (Bernhard 1982, 99–101; Bernhard 2006, 137; Bernhard 2007, 122–123). In addition, the archaeological single finds from the second half of the 5<sup>th</sup> century from rural areas which cannot be

precisely assigned to a late Roman or early medieval context show “Germanic” influences, especially from the “Elbe-Germanic”-Danubian context, which are seen by some researchers as remains from Alemanns (Koch 2008, 82; 109–110; Grünewald/Koch 2009). The finds from the earliest graves of the early medieval cemeteries show diverse influences. At Mainz-Finthen, the earliest finds are seen in a Rhine Frankish context (Engels 2008, 39; Grünewald/Koch 2009, 82). In more southern cemeteries such as Flomborn, objects of “Elbe-Germanic”-Danubian cultural influence have been found (Lange 2004; Grünewald/Koch 2009, 82). At Eppstein, Roman, Alemannic, Thuringian and “Elbe-Germanic” influences are visible (Engels 2012, 210–212). The isotopic analysis has revealed that the founder community in Eppstein was mainly comprised of individuals who had not spent their childhood or youth in the Upper Rhine Valley. Only two adult individuals show isotopic values indicating that they possibly have spent a part of their childhood or youth in the Upper Rhine Valley. The isotopic analysis has also shown that the settlers originated from diverse regions. For one young adult individual a childhood spent in a Mediterranean area is plausible. For most of the individuals, an origin from more eastern areas is likely because of the decreased  $\delta^{18}\text{O}$  values. Differentiating between Middle and Southwest Germany is difficult and other regions such as the Wetterau or the Odenwald region are also possible childhood residence areas. However, it cannot be excluded that they originated from the adjacent upland areas of the Saar-Nahe hills or the Palatinate Forest. This indicates that the foundation of the cemetery in Eppstein was connected to the immigration of individuals from different areas than the Upper Rhine Valley and local individuals played only a minor role, if any at all. Due to the young age of most of the individuals from these founder graves, it is rather unlikely that they are the former members of federates which served in the Roman army. They may be the descendants of these people but that they all reached the Upper Rhine Valley at such a young age, although rather unlikely, cannot be excluded.

The founder graves from Eppstein are heavily destroyed and it is likely that some of them date to the SD-phase 3 (ca. 480–510). The earliest graves which have been excavated at Bockenheim also appear at this time (Riemer pers. comm.). It is unclear if the Upper Rhine Valley was already under the influence of the Merovingian king Clovis, which is assumed to have taken place after the defeat of the Alemanns in 496 or finally in 506. Around the year 500, several new settlements, visible in the large number of newly founded cemeteries, were established. Rich founder graves,



which are especially known from the Rhine Hesse area, were interpreted as envoys of the Merovingian king who were brought to the Upper Rhine Valley with their families to consolidate power in the newly conquered regions (Grünewald/Koch 2009, 84–88; Leithäuser 2011, 224; Engels 2012, 196). However, an alternative interpretation is that local families might have sided with the Franks, adopted their identity by imitating the “elite” funeral rite –as known from the grave of Childeric in Tournai– to secure and show their power to the community (Halsall 2009; Theuvs 2009). From Eppstein and Bockenheim no such “elite” founder graves have been recovered. The earliest graves from Bockenheim which have been analysed are from female individuals. The graves are less destroyed and plundered than at Eppstein and show that two of the females were richly equipped with precious grave offerings and dress accessories. These two individuals, as well as a third woman, are of non-local origin. The fourth analysed founder grave of an older woman shows local isotopic values. The older age of the woman and the poor grave equipment, with only a single glass vessel, does not contradict the assumption that this woman represents a member of the former communities which settled in the Upper Rhine Valley during the second half of the 5<sup>th</sup> century. Furthermore, it is striking that none of the individuals from the founder graves at Bockenheim revealed radiogenic values above 0.71050 as at Eppstein. This might indicate that the newcomers at Bockenheim originate from different areas than the founder community at Eppstein. A tentative hint supporting this assumption might be the brooches of the women from Bockenheim, which indicate connections to western Frankish areas, while in Eppstein influences to areas east of the Rhine have been detected. Based on the differing isotopic values of the founder graves from Bockenheim, it can be stated that different areas of childhood residence are likely; including a local component, people originating from a warmer climate such as the Mediterranean, and people from a region with a wetter/cooler climate. This also indicates that the foundation of the Bockenheim cemetery was, based on the currently known excavated graves, not connected to the immigration of a group of individuals from a common area. It is more likely that the foreign women can be viewed in the context of an exogamous social structure. Connections between the two cemeteries are difficult to obtain because only one tooth per individual was sampled. However, a tentative connection could be indicated by the similar  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\delta^{18}\text{O}$  values of grave 488 from Bockenheim and burials 67C, 50 and 280 from Eppstein.

*Under the reign of the Merovingians*

At the beginning of the 6<sup>th</sup> century (SD-phase 4 = ca. 510–530), the Upper Rhine Valley was under the influence of the Merovingian king, namely Theudebert, Clovis' eldest son. It is generally assumed that at this time people were settled in the conquered areas to consolidate the power of the new ruler (e.g. Koch 2000). The numerous hand-made vessels of the 6<sup>th</sup> century which were found at several sites in the Upper Rhine Valley as well as other indications are seen as evidence of newcomers from Middle Germany (Wieczorek 1989; Wieczorek et al. 1996; Gross 1999; Koch 2000; Stauch 2004; Koch 2007; Leithäuser 2011; Engels 2012; Koch 2012a). This is also assumed for the cemeteries of Eppstein and Bockenheim (Engels 2005a 327–331; Engels 2012, 210–221; Riemer 2008, 154). At Eppstein, this period is generally characterised by a high rate of newcomers, including both sexes and all age groups, but mainly young adult and adult individuals. Only three of the eleven analysed individuals are of local origin. Two of these individuals are a young female and a young male and they might represent the first locally born generation. The hand-made vessel of Thuringian provenance indicates that at least the young female individual from grave 433 may represent a descendant of the newcomers. Based on the archaeological evidence, the influences from Middle Germany are not seen as a new immigration event but rather as continuity since the SD-phase 2–3 because these influences were already visible in the founder community (Engels 2005a 327–331; Engels 2012, 210–221). This question is difficult to answer based on the isotopic data because only one tooth per individual was sampled. However, based on the decreased  $\delta^{18}\text{O}$  values and radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values, which were also detected in the founder community, continuity cannot be excluded and is rather likely. For three of the non-local individuals with highly radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values but  $\delta^{18}\text{O}$  values which are indistinguishable from the local oxygen range (graves 431, 437, 35), an origin from Middle Germany, especially the Harz region, is not unlikely but cannot be proven with safety. For three other non-local individuals with  $^{87}\text{Sr}/^{86}\text{Sr}$  values which are almost similar to the local strontium range but slightly decreased  $\delta^{18}\text{O}$  values (graves 47, 49, 436), only an upland area or/and an area of colder climate as childhood residence area can be presumed. One individual (grave 48) shows an increased  $\delta^{18}\text{O}$  value which might indicate an origin from a warmer climatic area.

At Bockenheim, only three individuals have been analysed which can be dated to the beginning of the 6<sup>th</sup> century. Two of these individuals, a female child and a

young male, show local isotopic signatures, while an older female individual has local  $^{87}\text{Sr}/^{86}\text{Sr}$  but increased  $\delta^{18}\text{O}$  values which might be the result of a sampling bias due to the strongly abraded tooth sampled. Unfortunately, due to the small sample size it cannot be stated securely how far there was an absence of newcomers in contrast to Eppstein, where all except three individuals were of non-local origin.

*The row-grave cemeteries in the 6<sup>th</sup> century*

For the SD-phases 5 and 6 (ca. 530–555/580), the time between the second third of the 6<sup>th</sup> century and its latest phase, the data from all three cemeteries can be compared. By this time, the burial places had developed into typical row-grave cemeteries. The graves are heavily destroyed and plundered which reduces the possibility of making more detailed inferences about the social structures in general. However, burial mounds and graves with single objects which are typical for the upper social class can be clearly identified as “elite” burials at Eppstein and Dirmstein. For these cemeteries, new immigrants from the North Sea area are supposed, while in Bockenheim the continuing presence of hand-made vessels with parallels to the Thuringian area indicates the immigration of individuals from Middle Germany (Riemer 2008; Leithäuser 2011; Engels 2012).

A total of 46 individuals have been analysed from the Eppstein cemetery which date to the SD-phases 5 and 6. Only two hand-made vessels with parallels to the North Sea area, recovered in two child burials, indicate the presence of non-local individuals in the SD-phase 5. For the following period, no objects have been found which attest the presence of non-locals. However, the large increase of burials between the SD-phases 5 and 6 is connected to an immigration of newcomers in the second half of the 6<sup>th</sup> century. For the SD-phase 5, the isotopic analysis has revealed only 3 out of 15 individuals which spent their childhood in a different area than the Upper Rhine Valley. It is striking that the isotopic values of the burials with non-local individuals (413, 62, 67A) are not only similar to those of the preceding graves but that they are also in spatial connection to them. This continuity is most obvious in the grave of the older woman from grave 67A and the secondary burial of grave 67C with a similar  $^{87}\text{Sr}/^{86}\text{Sr}$  value. This means that a new immigration wave from the North Sea area, as indicated by two hand-made vessels from the child graves, is not visible by means of the isotopic data. However, there is the problem that the strontium and oxygen isotopic values of the North Sea area are similar to those of the Upper Rhine

Valley, which demonstrates the limitations of the isotopic analysis. For the SD-phase 6, where none of the grave offerings indicate non-local individuals, a total of 31 individuals have been analysed which with few exceptions are located in a spatially separated area in the northern part of the cemetery. It can be stated that the number of newcomers increases in comparison to the preceding SD-phase 5. Only two graves have more radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values than the local range and are in spatial connection to the other graves with more radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values from the preceding periods. These burials are probably the last individuals which can be connected to the older burials. It is striking that there are no individuals with decreased  $\delta^{18}\text{O}$  values as was the case in the preceding period. The immigration of individuals from an area with these  $\delta^{18}\text{O}$  values already ceased during the SD-phase 5. There are few other individuals of non-local origin from the SD-phase 6 who are scattered between the graves of the preceding period in the older burial area. A new immigration of a group of individuals of both sexes and all age groups excluding children has been detected, which is revealed by their less radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values. The remaining 20 individuals, including the grave under the burial mound and seven children, show values which are indicative of a childhood spent in the Upper Rhine Valley. Only one individual probably spent his childhood in a region of warmer climate.

At Bockenheim, for the SD-phase 5, hand-made vessels with parallels to the Thuringian area still indicate the presence of immigrants (Riemer pers. comm.). However, all of the six analysed individuals have local isotopic values. This high number of locals is in accordance with the results from Eppstein, where also only few non-locals have been detected. Furthermore, it is also similar to Eppstein that the number of non-local individuals increases in the SD-phase 6. Including the individuals that can only be dated roughly to the 6<sup>th</sup> century, there are six, maybe seven non-locals and nine individuals with isotopic values indistinguishable from the Upper Rhine Valley. Three of these individuals, consisting of an older male, an adult female individual and a child, form a separate cluster and originate from a region with less radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values. Two individuals originate from an area with a warmer climate and two other individuals have slightly decreased  $\delta^{18}\text{O}$  values indicating an origin from a higher or colder/wetter area than the Upper Rhine Valley.

At Dirmstein, the situation is different than at Bockenheim and Eppstein. No remains have been found which indicate the presence of migrants from the area of

Middle Germany. Instead, hand-made vessels as well as south-north orientated graves are supposed to represent the immigration of a group of people of the higher upper class from the North Sea area (Leithäuser 2011). From the SD-phases 5 and 5–6, 9 of the 14 analysed individuals are of non-local origin. In the following SD-phase 6, 4 out of 10 individuals are identified as immigrants. This is in contrast to Eppstein and Bockenheim, where more non-local individuals have been detected during the second half of the 5<sup>th</sup> century. The possible areas of origin of the non-locals are also different at Dirmstein in comparison to the other cemeteries. While at Eppstein and Bockenheim only few individuals have  $^{87}\text{Sr}/^{86}\text{Sr}$  values more radiogenic than the local range, at Dirmstein there are six individuals with more radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values. Four of them, including adult female and male individuals, form a cluster and probably migrated from the same area to the Upper Rhine Valley. The other two individuals have the most radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values of the complete sample set of this study. Two children and an additional individual with hand-made pottery and slightly elevated isotopic values might also be part of this group. Based on the more radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values and decreased  $\delta^{18}\text{O}$  values for most of the non-locals, an origin from a more eastern area with older geology than the Upper Rhine Valley is likely. An origin from the North Sea area cannot be proven by means of the isotopic analysis because this area has similar values as the Upper Rhine Valley. However, for the individuals with a non-local value, an origin from the North Sea area can be excluded. Similar to Eppstein and Bockenheim, there are individuals with local  $^{87}\text{Sr}/^{86}\text{Sr}$  values but increased  $\delta^{18}\text{O}$  values which are indicative of an origin from an area of warmer climate than the Upper Rhine Valley. It is striking that in the cemetery of Dirmstein there are no individuals with  $^{87}\text{Sr}/^{86}\text{Sr}$  values below the local range, as it is the case for Eppstein and Bockenheim. Only one individual of the complete sample set from Dirmstein has a  $^{87}\text{Sr}/^{86}\text{Sr}$  value below the local range but they already date to the SD-phase 5.

## 9.2 Final remarks

This study has shown that the isotopic analysis of strontium, oxygen and carbon is a valuable tool for the differentiation of local and non-local individuals in the Upper Rhine Valley. The most reliable tool for the detection of non-locals in the research area is the analysis of radiogenic strontium isotopes. The reason for this is the

relatively homogenous and young geology of the Upper Rhine Valley in comparison to the adjacent upland areas. Furthermore, it was possible to determine a relatively robust local strontium range for the northwestern Upper Rhine Valley and for each investigated site by means of the comparison and combination of different materials, species and approaches. This approach underlines the risk of the under- or overestimation of the local strontium range in studies using only single materials or approaches, which consequently distorts all conclusions concerning the archaeological questions of a study. However, as the local strontium signature of the Upper Rhine Valley is not unique and several non-local individuals with  $^{87}\text{Sr}/^{86}\text{Sr}$  values identical to the research area cannot be detected solely by strontium isotopes, it is important to include additional isotope systems for the detection of immigrants. As oxygen isotopes of meteoric water vary according to geographical and climatological factors, the analysis of  $\delta^{18}\text{O}$  of human tooth enamel is a suitable supplement to  $^{87}\text{Sr}/^{86}\text{Sr}$  because there is a decreasing northwest-southeast gradient of  $\delta^{18}\text{O}$  values in Europe. The local  $\delta^{18}\text{O}$  range of the research area was calculated from the mean values of individuals with local  $^{87}\text{Sr}/^{86}\text{Sr}$  values excluding early forming teeth. After removing outliers with  $\delta^{18}\text{O}$  values outside the mean  $\pm$  2SD, the range of  $\delta^{18}\text{O}$  values was still large with an amplitude of 1.7‰, but within the expected range for a community using the same drinking water sources. Furthermore, the range of  $\delta^{18}\text{O}$  values was consistent for each site. Reasons for the large variation within local communities are manifold, including temporal variation in climatic and hydrological conditions, weaning effects and various other cultural practices or biases as a result of the sampling technique. However, based on this  $\delta^{18}\text{O}$  range it was possible to detect several additional non-local individuals which were not detected with  $^{87}\text{Sr}/^{86}\text{Sr}$  alone.

Due to the numerous sources of variation, the unclear fractionation between carbonate and phosphate, and the not fully understood relationship between drinking water and human skeletal phosphate oxygen, as well as the errors which are associated with regression equations, it is generally recommended to rely on direct comparisons with published empirical  $\delta^{18}\text{O}$  values obtained from skeletal materials. However, in order to better estimate the origin of the non-local individuals and to make the data of this study comparable to other studies, the  $\delta^{18}\text{O}$  values were transformed into meteoric water  $\delta^{18}\text{O}$  values. It was detected that the  $\delta^{18}\text{O}$  values from the human tooth enamel samples are enriched in comparison to measured GNIP  $\delta^{18}\text{O}$  values of precipitation in Koblenz and Karlsruhe. This enrichment was also detected

in another study investigating an early medieval community (Hughes et al. 2014) and it is assumed that it is the result of human cultural behaviour such as the cooking and heating of food and beverages. This insight has implications for studies which rely on distribution maps for the identification of origin areas because increased  $\delta^{18}\text{O}$  values as a result of culturally mediated behaviour bear the risk of confounding geographical linkages between meteoric water and ingested  $\delta^{18}\text{O}$  values (Brettell et al. 2012b).

Carbon isotopes ( $\delta^{13}\text{C}$ ) are commonly measured from bone or dentine collagen samples in order to reconstruct dietary habits of human communities but also to detect immigrants (e.g. Hakenbeck et al. 2010). However, as carbon isotopes of the structural carbonate component are measured simultaneously to oxygen isotopes, they are also increasingly used in order to gain information about diet and mobility. In this study,  $\delta^{13}\text{C}$  values were helpful in order to detect non-local individuals because they most often supported the non-local origin indicated by  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\delta^{18}\text{O}$  values. In these cases,  $\delta^{13}\text{C}$  values were often decreased or increased with respect to the mean  $\delta^{13}\text{C}$  value  $\pm 2\text{SD}$ . Furthermore, increased  $\delta^{13}\text{C}$  values have revealed the consumption of a  $\text{C}_4$ -based diet but further work is needed to confirm these results.

Tests for diagenetic alteration have not been conducted. It is generally accepted that tooth enamel is more robust in comparison to bone and only minimally affected by contamination. Nevertheless, diagenetic alterations cannot be excluded in single cases, but are generally low because of the young age of the samples and the relatively good preservation, as well as the lower strontium concentrations of dental enamel in comparison to dentine. Furthermore, the pretreatment effects had only minor influence on the  $\delta^{18}\text{O}$  values and the sequential cattle samples have also shown the expected seasonal patterns attesting the excellent preservation of the teeth.

The analysis of strontium, oxygen and carbon isotopes of human tooth enamel has revealed a large number of non-local individuals in the Upper Rhine Valley during the late 5<sup>th</sup> and 6<sup>th</sup> centuries. At least 53 out of a total of 120 investigated individuals show indications of having obtained food and drinking water from a different area than the Upper Rhine Valley. The 67 individuals whose isotopic values are indistinguishable from the local oxygen and strontium ranges of the Upper Rhine Valley included 21 children. It cannot be stated that women were more mobile than men indicating an exogamous social structure. There are also no differences between age groups, apart from the fact that children were less mobile (four non-local vs. 21 local children) than other age groups as expected. In the earliest SD-phase 2–3

between the late 5<sup>th</sup> and the beginning of the 6<sup>th</sup> century most of the individuals were of non-local origin. This was also the case in the SD-phase 4/4–5 in the first half of the 6<sup>th</sup> century. In the SD-phase 5/5–6 the number of locals increases, while the number of non-locals started to increase during the SD-phase 6/6–7 during the second half of the 6<sup>th</sup> century. Based on the heavy destruction and plundering of the graves no secure statements can be made regarding whether individuals of a higher social rank were more mobile than those of the lower social class. However, it is remarkable that the few identified individuals belonging to the uppermost social class (quality group C after Christlein, n = 4 excluding Bockenheim because no data were available) spent at least their youth in the Upper Rhine Valley. Furthermore, it was possible to show that not only individual mobility occurred but also that groups of people from the same area immigrated to the Upper Rhine Valley, which might represent administrated settlement processes in the name of the Frankish king. Furthermore, it has been shown that the establishment of a new burial rite in the late 5<sup>th</sup> century was mainly connected to individuals from diverse regions that had not spent their childhood in the Upper Rhine Valley. Local communities played, only a minor role, if any at all. It can be stated that foreign hand-made pottery in the Upper Rhine Valley, which was not robbed in comparison to the precious metal objects because of its minor monetary value, indicate the presence of non-local individuals. However, only in single cases do foreign burial practices or foreign objects also reflect a foreign identity for the buried individual. This underpins the fact that foreign elements in the burial rite including hand-made pottery are rather an indirect indicator for the origin of the family and relatives of the deceased person, rather than a direct proof of immigration. This assumption is also confirmed by the observation that hand-made vessels are often found in graves of children and young adult individuals. The presence of these immigrated groups is only visible for a short time, because they were adapted to the typical funeral tradition very quickly.

Based on archaeological investigations of the hand-made vessels it was assumed that individuals and groups immigrated especially from Middle Germany and the North Sea area (Wieczorek 1989; Schenk 1998; Gross 1999; Koch 2000; Leithäuser 2011; Engels 2012). The isotopic analysis of human teeth is limited as a result of the fact that the estimated local ranges of the investigated areas are not unique. Therefore, it is only possible to exclude certain provenance areas for non-local individuals. Since the Upper Rhine Valley has similar values to the North Sea



area, including northern Germany, the Netherlands, and Belgium as well as southwestern Britain, it is not possible to identify immigrants from this area. However, based on the results of the Dirmstein cemetery, for which an origin from the North Sea area was supposed, the isotopic analysis has revealed that most of the non-local individuals showed strontium and oxygen values which are typical for regions with older geology as well as a more continental climate. This observation excludes immigration from the North Sea area for most of the individuals and rather indicates an origin from a more eastern area than the Upper Rhine Valley. This was also the case for several of the earliest graves from the Eppstein cemetery and therefore immigration from Middle Germany cannot be excluded. Furthermore, the heterogeneous isotopic values indicate diverse provenance areas for the non-local individuals, including areas of warmer climate than the Upper Rhine Valley such as the Mediterranean. In the second half of the 6<sup>th</sup> century in particular, immigrations from different areas than in the preceding periods occur. These new immigrations would have been undetected without the isotopic analysis because the archaeological record revealed no indicators for the presence of non-local individuals. This is mainly the result of the standardised burial rite of the row-grave cemeteries but also due to the heavy plundering of the graves.

To conclude, this research study has shown that during the late 5<sup>th</sup> and 6<sup>th</sup> centuries the Upper Rhine Valley was characterised by heterogeneous and dynamic settlement communities indicating an intensive cultural contact zone.

## V. Abstract/Zusammenfassung

The 5<sup>th</sup> and 6<sup>th</sup> centuries were a period characterised by complex and drastic transformations in the political, social and cultural landscapes of Europe. Non-Roman groups increasingly invaded the gradually dissolving Western Roman Empire which was finally replaced by independent “Romano-barbarian kingdoms”. In the 6<sup>th</sup> century, the Franks from the Merovingian dynasty are the main power in Central Europe and eventually dominated a territory from east of the Rhine to southern France. However, written sources are uninformative regarding how far these overall socio-political dynamics affected local communities in the northeastern Rhine areas. The archaeological record indicates profound cultural transformations during the 5<sup>th</sup> and 6<sup>th</sup> centuries, which includes the use of a new burial practice. In many regions of Western and Central Europe, people started to bury their dead at new burial grounds in west-east oriented inhumation graves with especially rich grave goods. Traditional archaeological approaches attribute the rich burials to the immigration of “Germanic” groups. Single grave goods, combinations of grave goods and other elements of the funeral rite have been used to prove the arrival of foreign groups and individuals. Newer approaches criticise a sheer “migrational” explanation and consider the creation of a new funeral rite as a cultural reorientation by the local communities in response to the social and political dynamics of the time.

This study employs an interdisciplinary approach in order to investigate how far the foundation of the early medieval cemeteries as well as foreign grave goods can be connected to the immigration of individuals or groups. The investigations were conducted on three cemeteries located on the western bank of the northern Upper Rhine Valley. Based on written and archaeological records, it is assumed that the burial communities in this former frontier zone were comprised of individuals and groups with different origins. Hand-made pottery as a grave offering indicates immigration from the North Sea area as well as Middle Germany. The continued presence of Roman structures during the second half of 5<sup>th</sup> century suggests that local communities were present when the new funeral rite was created.

In order to differentiate between local and non-local individuals interred in burial plots, strontium ( $^{87}\text{Sr}/^{86}\text{Sr}$ ), oxygen ( $\delta^{18}\text{O}$ ) and carbon ( $\delta^{13}\text{C}$ ) isotope analysis were conducted on a total of 137 human tooth enamel samples from 120 individuals dating to the late 5<sup>th</sup> and 6<sup>th</sup> centuries. In addition, the biologically available  $^{87}\text{Sr}/^{86}\text{Sr}$

signature of the Upper Rhine Valley was estimated based on the analysis of 98 samples, including faunal enamel, faunal and human dentine, eggshells, soil, and water samples. The isotopic results of the human individuals, in combination with the archaeological and anthropological data, has shown that the foundation of the investigated cemeteries was connected to individuals from diverse regions who had not spent their childhood in the Upper Rhine Valley and that local individuals played only a minor role. Hand-made pottery found in graves also has stylistic parallels to material from the North Sea area and Middle Germany, providing additional support for the presence of migrants; however, the isotopic results cannot directly demonstrate the movement of individuals from the North Sea area to the Rhine and the presence of people from Middle Germany cannot be excluded. In the 6<sup>th</sup> century, additional newcomers were identified isotopically who would have been otherwise undetected based on the archaeological evidence. While the graves of the late 5<sup>th</sup> and the early 6<sup>th</sup> century indicate immigrations from more eastern areas, the graves of the late 6<sup>th</sup> century show increasing influences from more western areas. Single individuals show isotopic values indicating an origin from the Mediterranean area. In addition to individual mobility, the immigration of smaller groups has been detected which might represent administrated settlement processes in the name of the Frankish king. The multiple waves of mobility and immigration indicated by the isotopic and material cultural data presented here suggests that the Upper Rhine Valley was a region characterised by culturally heterogeneous and dynamic settlement communities typical of an intensive cultural contact zone.

## **Zusammenfassung**

Das 5. und 6. Jahrhundert n. Chr. in Europa ist geprägt von komplexen und tiefgreifenden Transformationen in fast allen Lebensbereichen. Nicht-römische Gruppen dringen vermehrt in das sich allmählich auflösende Weströmische Reich ein, das schließlich von „Romano-Barbarischen Königreichen“ abgelöst wird. Im 6. Jahrhundert n. Chr. stellen die Franken vom Geschlecht der Merowinger den größten Machtfaktor in Mitteleuropa dar und dominieren schließlich über ein Gebiet von Mitteldeutschland bis Südfrankreich. Inwiefern diese übergeordneten Veränderungen jedoch die lokalen Bevölkerungen betrafen, ist unbekannt. Die archäologischen Hinterlassenschaften zeugen ebenfalls von tiefgreifenden Transformationen am Übergang zwischen Spätantike und Frühmittelalter. Eine dieser Veränderungen war die Erschaffung einer neuen Bestattungssitte. In zahlreichen Regionen West- und Mitteleuropas begannen die Menschen ihre Toten in neu gegründeten Gräberfeldern in West-Ost-ausgerichteten Gräbern und mit reichen Beigaben zu bestatten. Traditionelle Interpretationen beziehen diese Bestattungssitte auf die Einwanderung germanischer Gruppen. Einzelne Grabbeigaben, Kombinationen von Grabbeigaben sowie andere Elemente des Bestattungsbrauchtums wurden dafür verwendet, die Anwesenheit von fremden Gruppen und Individuen nachzuweisen. Neuere Ansätze kritisieren diese rein „migrationistische“ Deutung und sehen in der Erschaffung einer neuen Bestattungssitte eher eine kulturelle Neuorientierung lokaler Gemeinschaften als Reaktion auf die Krisenzeit.

In dieser Studie wurde ein interdisziplinärer Ansatz verwendet, um zu untersuchen, inwiefern die Entstehung neuer Gräberfelder sowie fremde Elemente im Bestattungsbrauchtum mit der Anwesenheit von eingewanderten Personen und/oder Gruppen verbunden waren. Die Untersuchungen wurden an drei Gräberfeldern auf der westlichen Seite des nördlichen Oberrheins durchgeführt. In diesem ehemaligen Grenzgebiet kann aufgrund von schriftlichen und archäologischen Quellen davon ausgegangen werden, dass sich die Bevölkerung aus Individuen unterschiedlicher Herkunft zusammensetzte. Handgemachte Keramik als Grabbeigabe deutet auf eine Einwanderung vor allem aus dem Nordseeküstengebiet sowie Mitteldeutschland hin. Da nachgewiesen werden konnte, dass römische Strukturen noch bis in die 2. Hälfte des 5. Jahrhunderts n. Chr. vorhanden waren, kann davon ausgegangen werden, dass auch lokale Gemeinschaften anwesend waren als die neue Bestattungssitte eingeführt

wurde. Zur Unterscheidung von lokalen und eingewanderten Personen wurden Strontium- ( $^{87}\text{Sr}/^{86}\text{Sr}$ ), Sauerstoff- ( $\delta^{18}\text{O}$ ) sowie Kohlenstoff-Isotopenuntersuchungen ( $\delta^{13}\text{C}$ ) an insgesamt 137 menschlichen Zahnschmelzproben von 120 Individuen durchgeführt, die aus Gräbern des späten 5. und 6. Jahrhunderts n. Chr. stammen. Zusätzlich konnte anhand von 98 Proben, darunter Zahnschmelzproben von Tieren, Dentinproben, Eierschalen, sowie Boden und Wasserproben, die lokale bioverfügbare Strontium-Isotopensignatur des nördlichen Oberrheingebietes bestimmt werden. Durch die Kombination der Ergebnisse der Isotopenanalysen mit den archäologischen und anthropologischen Daten konnte nachgewiesen werden, dass die Gründung der untersuchten Gräberfelder mit Individuen aus verschiedenen Regionen verbunden war, die ihre Kindheit nicht im Oberrheingebiet verbracht haben und lokale Individuen dabei nur eine geringe Rolle spielten. Es konnte festgestellt werden, dass über den gesamten untersuchten Zeitraum eine hohe Anzahl von Einwanderern vorhanden waren. Die handgemachten Gefäße mit Parallelen aus Gebieten des Nordseeküstenraums und Mitteldeutschland sind ein indirekter Indikator für die Anwesenheit eingewanderter Personengruppen. Allerdings konnten Einwanderungen aus dem Nordseegebiet mittels Isotopenanalysen nicht nachgewiesen werden, wohingegen Migranten aus dem mitteldeutschen Raum nicht ausgeschlossen werden können. Im 6. Jahrhundert n. Chr. konnten zusätzliche Neankömmlinge festgestellt werden, die anhand der archäologischen Hinterlassenschaften nicht sichtbar waren. Während die Gräber des späten 5. und frühen 6. Jahrhunderts n. Chr. eher auf eine Herkunft aus östlicheren Gebieten hinweisen, sind für das fortgeschrittene 6. Jahrhundert n. Chr. vermehrt Einflüsse aus westlichen Gebieten feststellbar. Vereinzelt weisen Personen Isotopenwerte auf, die auf eine Herkunft aus dem mediterranen Gebiet hindeuten. Neben der Mobilität einzelner Individuen konnte auch die Einwanderung kleinerer Gruppen nachgewiesen werden, die auf einen administrativ gesteuerten Besiedlungsprozess hinweisen könnten. Darüber hinaus kann festgehalten werden, dass bei den drei untersuchten Gräberfeldern Einwanderungen aus unterschiedlichen Regionen stattgefunden haben, was hervorhebt, dass das Oberrheingebiet auch im frühen Mittelalter als kulturelle Kontaktzone von heterogenen und dynamischen Siedlungsgemeinschaften geprägt war.

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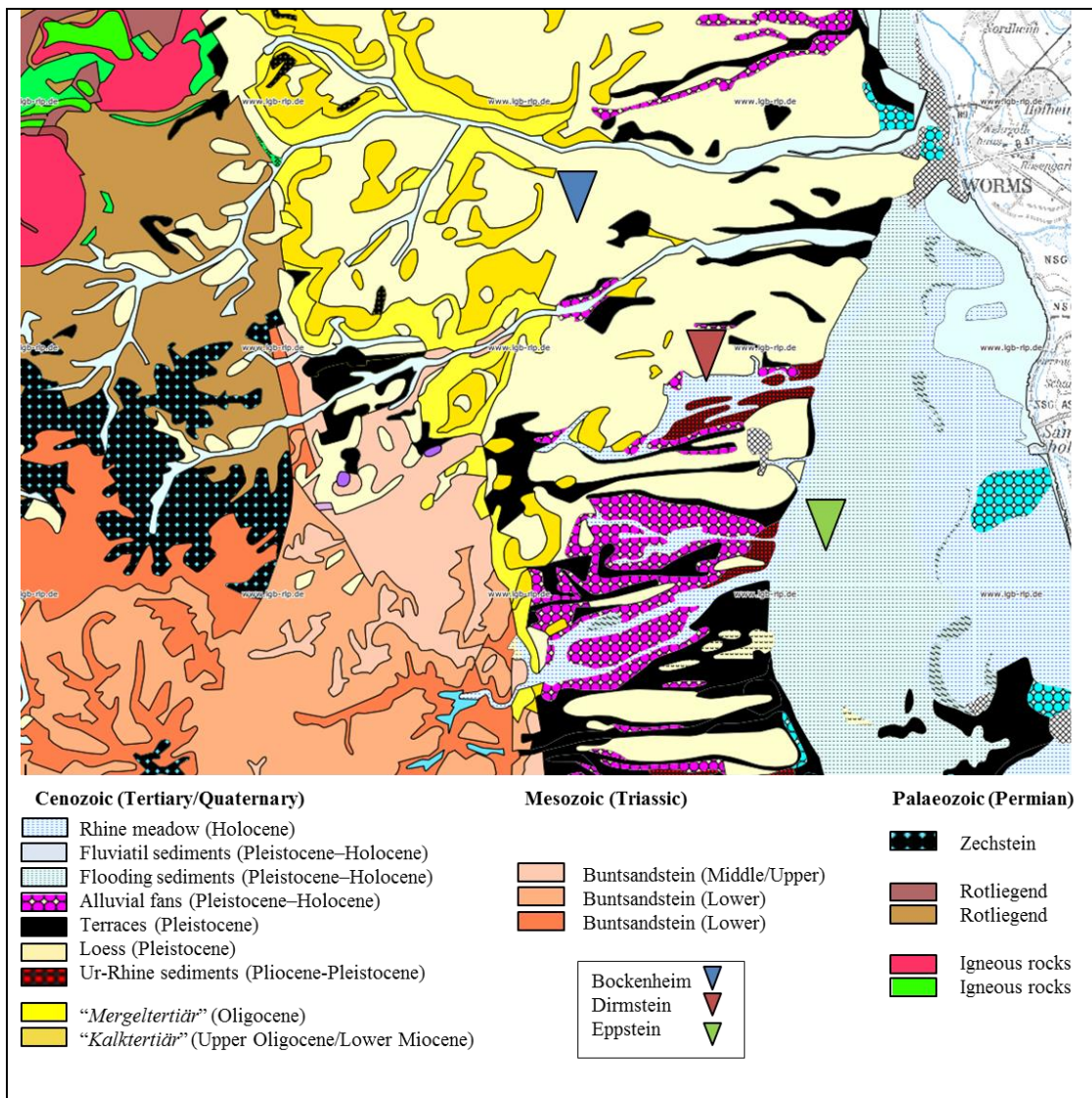
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## VII. Appendix

### 10 Figures and tables



**Fig. 10.1. Geology of the Upper Rhine Valley**  
(map basis: GÜK 300, Rhineland-Palatinate State Office for Geology and Mining<sup>19</sup>).

<sup>19</sup> [http://mapclient.lgb-rlp.de/?app=lgb&view\\_id=4](http://mapclient.lgb-rlp.de/?app=lgb&view_id=4) (13.01.2014).

**Tab. 10.1. Descriptive statistics of  $^{87}\text{Sr}/^{86}\text{Sr}$  and Sr ppm from the complete human sample set.**

	$^{87}\text{Sr}/^{86}\text{Sr}$		ppm	
	Statistic	Std. Error	Statistic	Std. Error
<b>Mean</b>	.7101020	.00022285	128.00	4.366
<b>95% Confidence Interval for Mean</b>				
<b>Lower Bound</b>	.7096613	119.37		
<b>Upper Bound</b>	.7105427	136.63		
<b>5 % Trimmed Mean</b>	.7096849		124.53	
<b>Median</b>	.7095110		120.00	
<b>Variance</b>	.000		2,611.353	
<b>Std. Deviation</b>	.00260842		51.101	
<b>Minimum</b>	.70819		36	
<b>Maximum</b>	.72938		326	
<b>Range</b>	.02119		290	
<b>Interquartile Range</b>	.00072		60	
<b>Skewness</b>	5.080	.207	1.122	.207
<b>Kurtosis</b>	30.078	.411	1.733	.411

**Tab. 10.2. Test of normality for  $^{87}\text{Sr}/^{86}\text{Sr}$  and Sr ppm from the complete human sample set.**

	Kolmogorov-Smirnov <sup>a</sup>			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
$^{87}\text{Sr}/^{86}\text{Sr}$	.328	137	.000	.448	137	.000
ppm	.105	137	.001	.934	137	.000

a. Lilliefors Significance Correction

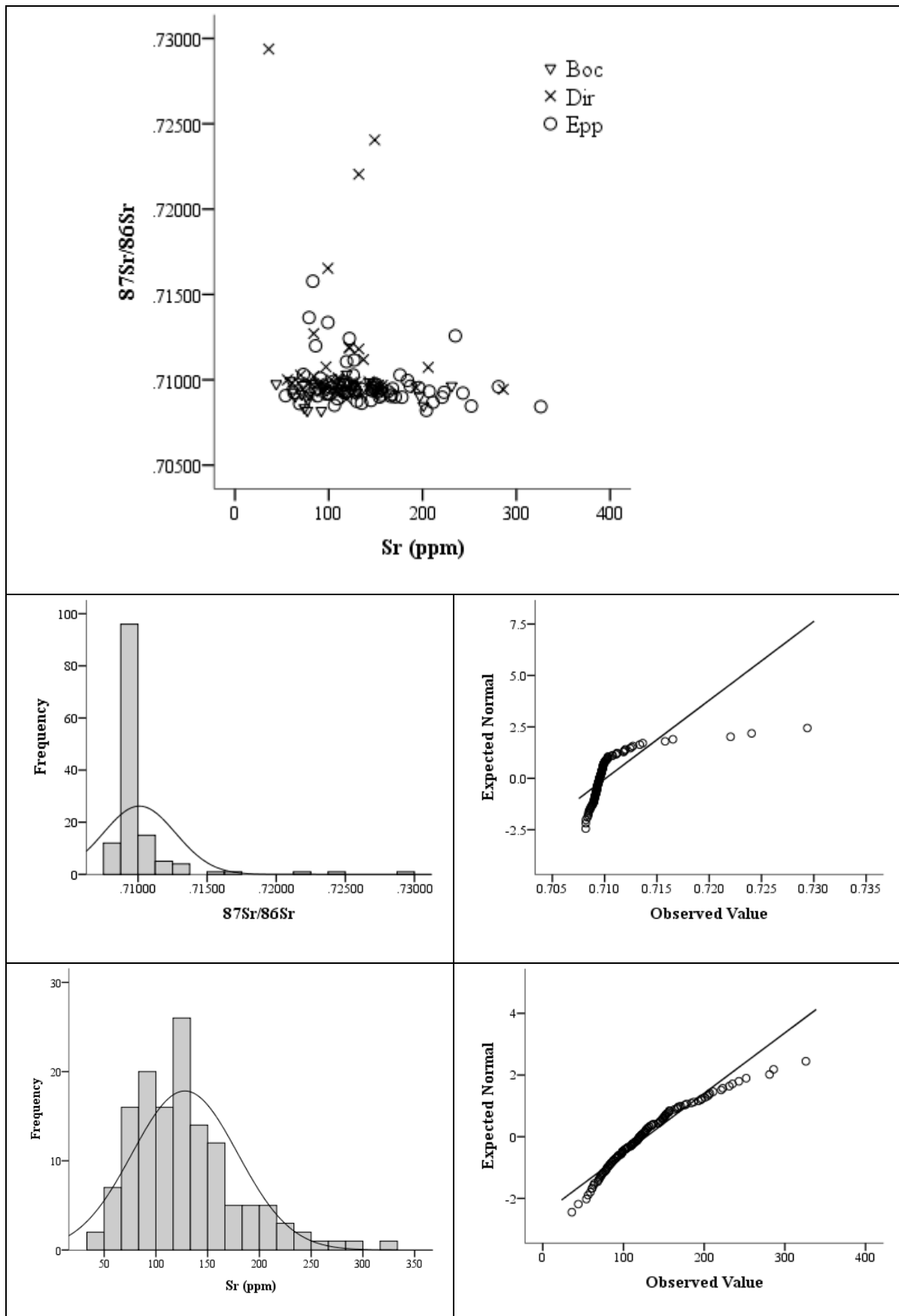
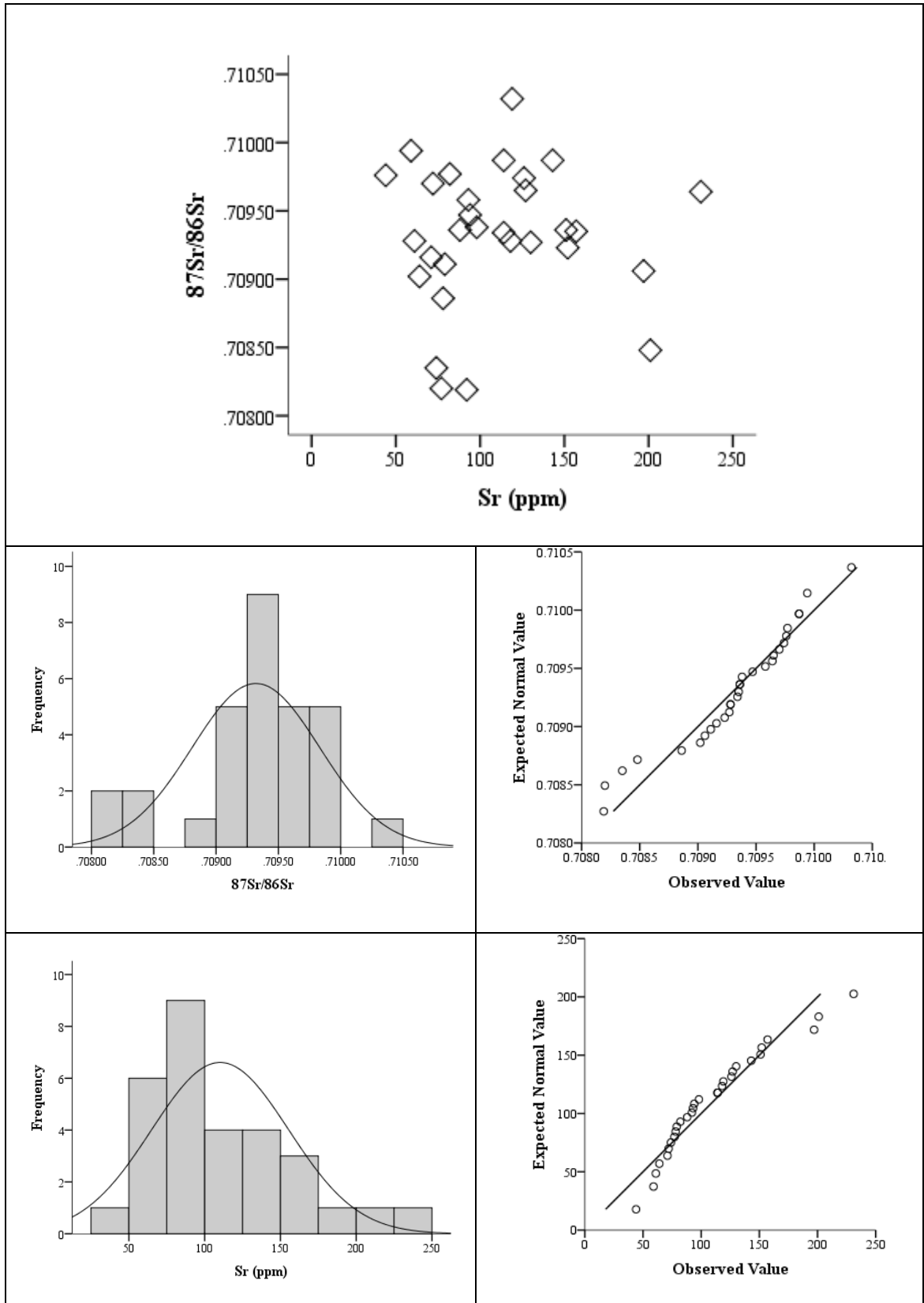


Fig. 10.2. Graphical description of  $^{87}\text{Sr}/^{86}\text{Sr}$  and Sr ppm from the complete human sample set.



**Fig. 10.3. Graphical description of  $^{87}\text{Sr}/^{86}\text{Sr}$  and Sr ppm from Bockenheim.**

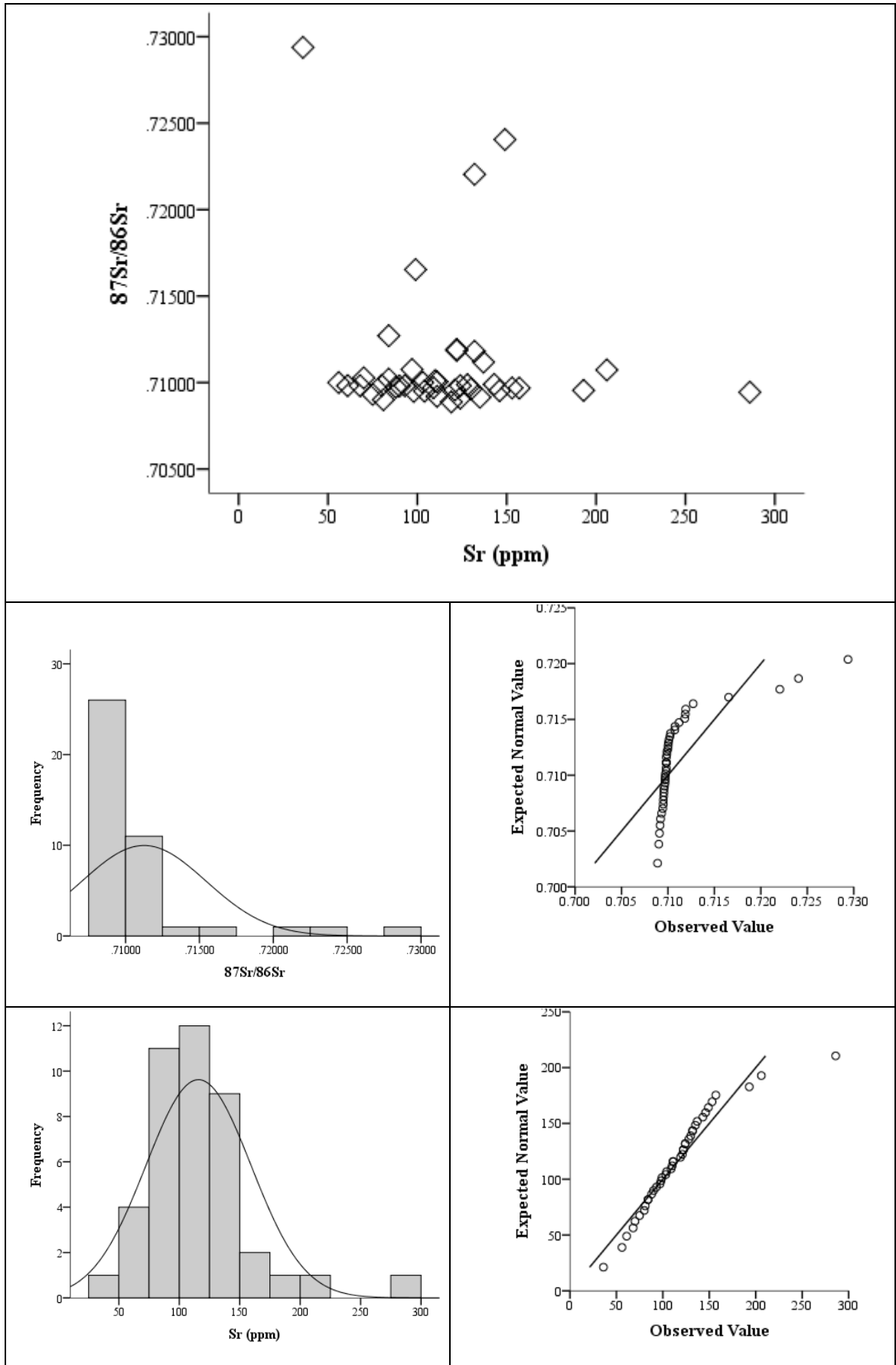


Fig. 10.4. Graphical description of  $^{87}\text{Sr}/^{86}\text{Sr}$  and Sr ppm from Dirmstein.



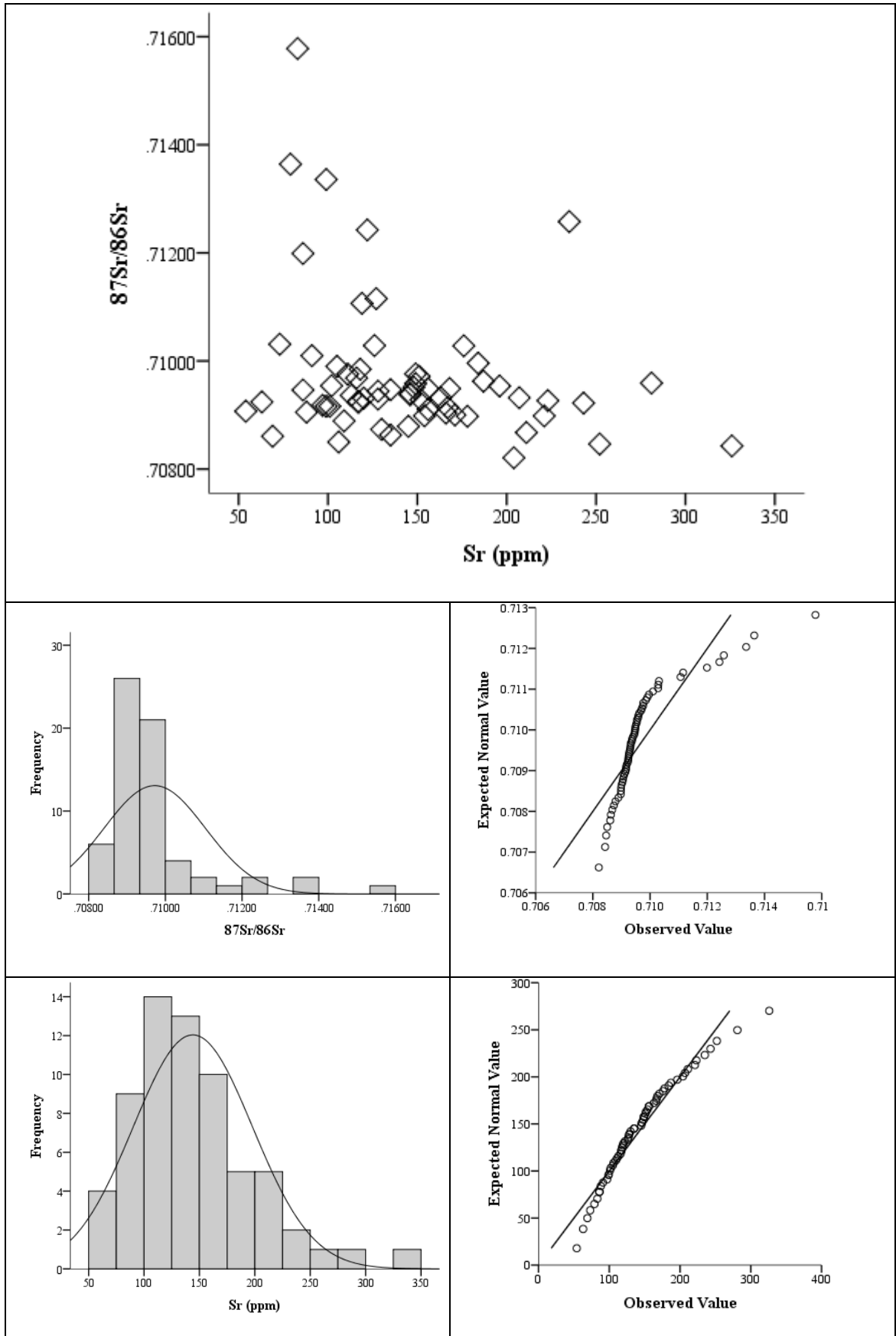
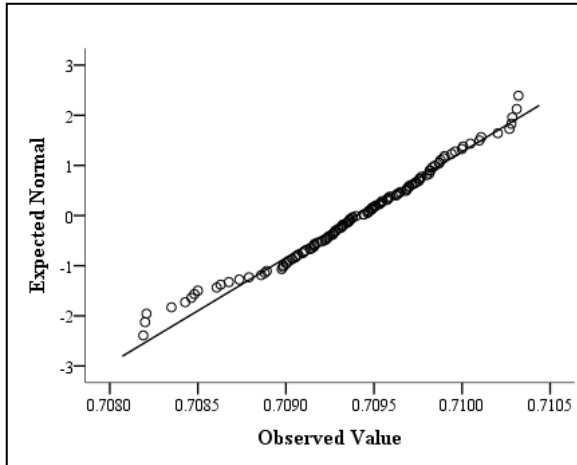
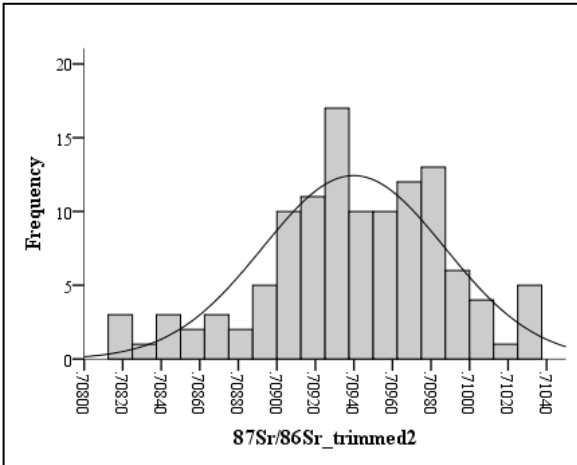
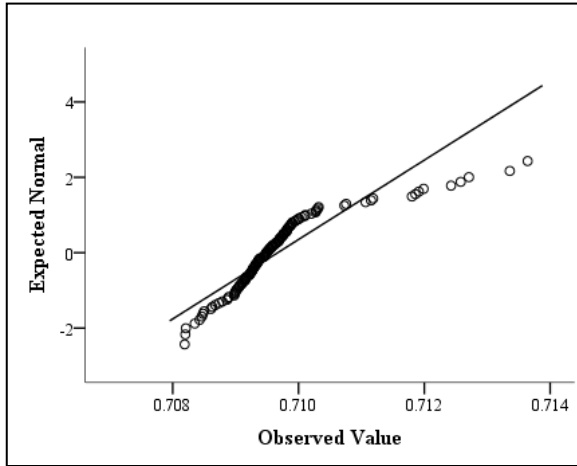
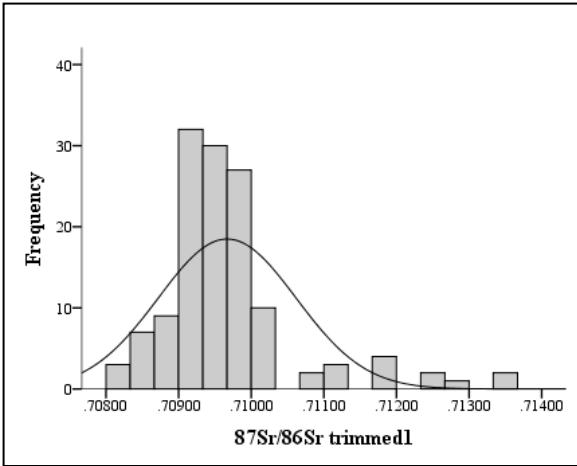
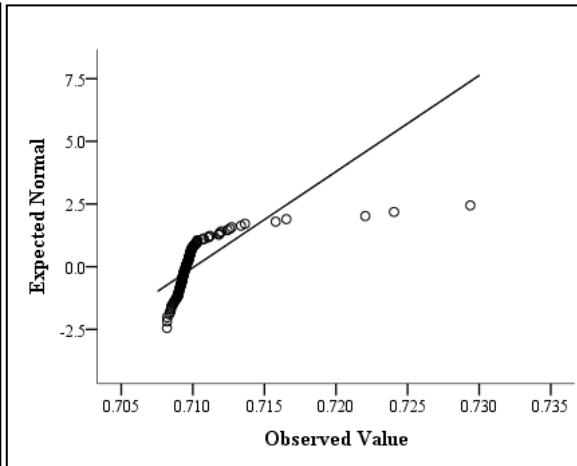
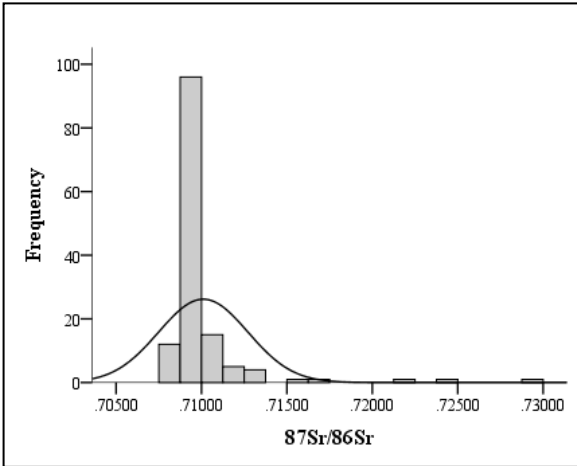


Fig. 10.5. Graphical description of  $^{87}\text{Sr}/^{86}\text{Sr}$  and Sr ppm from Eppstein.

**Tab. 10.3. Descriptive statistics of  $^{87}\text{Sr}/^{86}\text{Sr}$  trimmed data sets.**

$^{87}\text{Sr}/^{86}\text{Sr}$	Complete	Trimmed1	Trimmed2	Trimmed3	Trimmed4	Trimmed5
<b>N</b>	137	132	118	<b>105</b>	96	88
<b>Mean</b>	.7101020	.7096681	.7093986	<b>.7094357</b>	.7094841	.7094690
<b>SE of Mean</b>	.00022285	.00008261	.00004357	<b>.00003474</b>	.00003072	.00002848
<b>Median</b>	.7095110	.7094895	.7094190	<b>.7094410</b>	.7094775	.7094695
<b>Mode</b>	Multiple	Multiple	Multiple	<b>Multiple</b>	Multiple	Multiple
<b>SD</b>	.00260842	.00094917	.00047329	<b>.00035601</b>	.00030101	.00026717
<b>Skewness</b>	5.080	1.939	-.421	<b>-.136</b>	.130	.038
<b>SE Skewness</b>	.207	.211	.223	<b>.236</b>	.246	.257
<b>Kurtosis</b>	30.078	4.799	.090	<b>-.540</b>	-.979	-1.133
<b>SE Kurtosis</b>	.411	.419	.442	<b>.467</b>	.488	.508
<b>Range</b>	.02119	.00545	.00213	<b>.00160</b>	.00113	.00096
<b>Minimum</b>	.70819	.70819	.70819	<b>.70861</b>	.70898	.70900
<b>Maximum</b>	.72938	.71364	.71032	<b>.71020</b>	.71011	.70996
<b>Shapiro-Wilk</b>	.448	.814	.979	<b>.989</b>	.970	.962
<b>df</b>	137	132	118	<b>105</b>	96	88
<b>Sig.</b>	.000	.000	.057	<b>.549</b>	.026	.010



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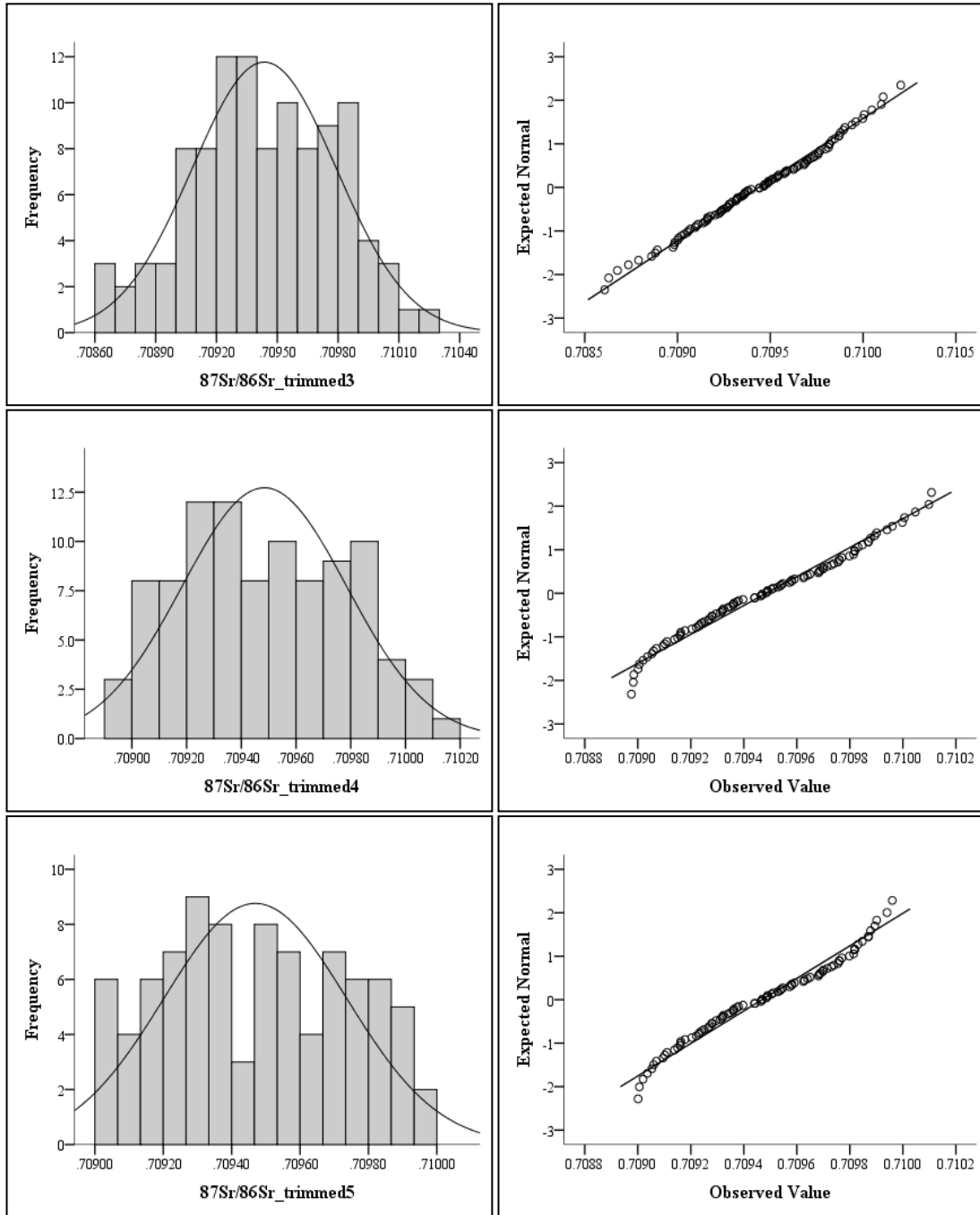


Fig. 10.6. Graphical description of  $^{87}\text{Sr}/^{86}\text{Sr}$  trimmed data sets.

**Tab. 10.4. Legend for the different protocols from pretreatment experiment II.**

AA	untreated (60°C)
B	3% NaOCl 30min
BB	3% NaOCl 24h
C	0,1 M acetic acid 10min
CC	0,1 M acetic acid 2h
D	3% NaOCl 30min/0,1 M acetic acid 10 min
DD	3% NaOCl 24h/0,1 M acetic acid 2h

**Tab. 10.5. Results of pretreatment experiment II.**

No	Sample	Protocol	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\Delta\delta^{13}\text{C}$	$\Delta\delta^{18}\text{O}$
1	Dir-24-M3	AA	-12.04	-4.82	0.00	0.00
1	Dir-24-M3	B	-11.91	-4.56	0.13	<b>0.26</b>
1	Dir-24-M3	BB	-11.89	-4.70	0.15	0.12
1	Dir-24-M3	C	-12.04	-4.80	-0.01	0.02
1	Dir-24-M3	CC	-12.13	-4.67	-0.09	0.14
1	Dir-24-M3	D	-12.19	-4.87	-0.16	-0.05
1	Dir-24-M3	DD	-12.13	-4.65	-0.09	0.16
2	Dir-25b-M3	AA	-12.99	-4.87	0.00	0.00
2	Dir-25b-M3	B	-13.02	-4.75	-0.03	0.12
2	Dir-25b-M3	BB	-12.92	-4.87	0.07	0.01
2	Dir-25b-M3	C	-13.01	-4.70	-0.02	0.17
2	Dir-25b-M3	CC	-13.03	-4.64	-0.04	<b>0.23</b>
2	Dir-25b-M3	D	-13.09	-4.58	-0.10	<b>0.29</b>
2	Dir-25b-M3	DD	-13.25	-5.01	<b>-0.26</b>	-0.14
3	Dir-26-M3	AA	-12.80	-4.71	0.00	0.00
3	Dir-26-M3	B	-12.56	-4.70	<b>0.23</b>	0.01
3	Dir-26-M3	BB	-12.64	-4.75	0.15	-0.04
3	Dir-26-M3	C	-12.95	-4.72	-0.15	-0.01
3	Dir-26-M3	CC	-12.72	-4.53	0.08	0.18
3	Dir-26-M3	D	-12.88	-4.67	-0.09	0.04
3	Dir-26-M3	DD	-12.91	-4.46	-0.12	<b>0.25</b>
4	Dir-47-M3	AA	-13.73	-4.47	0.00	0.00
4	Dir-47-M3	B	-13.71	-4.22	0.02	0.25
4	Dir-47-M3	BB	-13.74	-4.49	-0.01	-0.02
4	Dir-47-M3	C	-13.72	-4.45	0.01	0.03
4	Dir-47-M3	CC	-13.82	-4.20	-0.09	<b>0.27</b>
4	Dir-47-M3	D	-13.74	-4.51	-0.01	-0.04
4	Dir-47-M3	DD	-13.85	-4.42	-0.12	0.05
5	Dir-244-M3	AA	-13.88	-5.77	0.00	0.00
5	Dir-244-M3	B	-13.78	-5.83	0.10	-0.05
5	Dir-244-M3	BB	-14.11	-5.72	<b>-0.24</b>	0.05
5	Dir-244-M3	C	-14.13	-5.80	<b>-0.26</b>	-0.03
5	Dir-244-M3	CC	-14.22	-5.88	<b>-0.34</b>	-0.11
5	Dir-244-M3	D	-13.93	-5.69	-0.05	0.08
5	Dir-244-M3	DD	-14.21	-5.56	<b>-0.34</b>	<b>0.21</b>
6	Epp-37-M2	AA	-13.79	-4.02	0.00	0.00
6	Epp-37-M2	B	-13.78	-4.13	0.02	-0.11

6	Epp-37-M2	BB	-13.87	-3.96	-0.08	0.06
6	Epp-37-M2	C	-13.93	-4.05	-0.14	-0.03
6	Epp-37-M2	CC	-13.78	-3.88	0.02	0.14
6	Epp-37-M2	D	-13.73	-4.02	0.06	0.00
6	Epp-37-M2	DD	-13.79	-4.05	0.00	-0.04
7	Epp-62-M2	AA	-13.13	-4.32	0.00	0.00
7	Epp-62-M2	B	-13.12	-4.28	0.02	0.03
7	Epp-62-M2	BB	-13.18	-4.35	-0.05	-0.03
7	Epp-62-M2	C	-13.30	-4.26	-0.16	0.06
7	Epp-62-M2	CC	-13.29	-4.21	-0.16	0.11
7	Epp-62-M2	D	-13.32	-4.31	-0.19	0.00
7	Epp-62-M2	DD	-13.25	-4.43	-0.12	-0.12
8	Epp-25-M2	AA	-13.76	-4.92	0.00	0.00
8	Epp-25-M2	B	-13.80	-4.88	-0.04	0.04
8	Epp-25-M2	BB	-13.73	-4.83	0.02	0.09
8	Epp-25-M2	C	-13.80	-4.90	-0.05	0.02
8	Epp-25-M2	CC	-13.88	-4.96	-0.12	-0.04
8	Epp-25-M2	D	-13.89	-4.90	-0.13	0.01
8	Epp-25-M2	DD	-13.89	-5.04	-0.13	-0.13
9	Epp-246-M2	AA	-13.47	-3.62	0.00	0.00
9	Epp-246-M2	B	-13.44	-3.60	0.03	0.03
9	Epp-246-M2	BB	-13.52	-3.45	-0.05	0.17
9	Epp-246-M2	C	-13.54	-3.57	-0.07	0.06
9	Epp-246-M2	CC	-13.53	-3.55	-0.06	0.07
9	Epp-246-M2	D	-13.50	-3.53	-0.03	0.09
9	Epp-246-M2	DD	-13.41	-3.60	0.07	0.02
10	Epp-48-M2	AA	-12.71	-2.61	0.00	0.00
10	Epp-48-M2	B	-12.70	-2.44	0.01	0.17
10	Epp-48-M2	BB	-12.52	-2.55	0.19	0.06
10	Epp-48-M2	C	-12.70	-2.31	0.01	0.30
10	Epp-48-M2	CC	-12.75	-2.43	-0.05	0.18
10	Epp-48-M2	D	-12.90	-2.85	-0.19	-0.24
10	Epp-48-M2	DD	-12.90	-2.59	<b>-0.20</b>	0.02
11	Bo-457-M(2)	AA	-13.69	-4.74	0.00	0.00
11	Bo-457-M(2)	B	-13.70	-4.88	-0.01	-0.13
11	Bo-457-M(2)	BB	-13.72	-4.89	-0.04	-0.15
11	Bo-457-M(2)	C	-13.67	-4.73	0.01	0.01
11	Bo-457-M(2)	CC	-13.74	-4.81	-0.05	-0.06
11	Bo-457-M(2)	D	-13.59	-4.59	0.10	0.15
11	Bo-457-M(2)	DD	-13.81	-4.80	-0.13	-0.06
12	Bo-22-M2	AA	-13.51	-3.97	0.00	0.00
12	Bo-22-M2	B	-13.61	-4.16	-0.10	-0.19
12	Bo-22-M2	BB	-13.51	-4.16	-0.01	-0.19
12	Bo-22-M2	C	-13.64	-4.08	-0.13	-0.11
12	Bo-22-M2	CC	-13.44	-3.96	0.07	0.01
12	Bo-22-M2	D	-13.51	-3.99	0.00	-0.02
12	Bo-22-M2	DD	-13.58	-4.03	-0.07	-0.05

13	Bo-396-M2	AA	-13.75	-4.91	0.00	0.00
13	Bo-396-M2	B	-13.71	-4.82	0.04	0.09
13	Bo-396-M2	BB	-13.64	-4.78	0.12	0.14
13	Bo-396-M2	C	-13.69	-4.77	0.07	0.14
13	Bo-396-M2	CC	-13.81	-4.72	-0.05	0.19
13	Bo-396-M2	D	-13.79	-4.73	-0.04	0.18
13	Bo-396-M2	DD	-13.86	-4.82	-0.11	0.09
14	Bo-474-M2	AA	-12.76	-4.25	0.00	0.00
14	Bo-474-M2	B	-12.78	-4.26	-0.01	-0.01
14	Bo-474-M2	BB	-12.83	-4.34	-0.06	-0.09
14	Bo-474-M2	C	-12.85	-4.35	-0.09	-0.10
14	Bo-474-M2	CC	-12.89	-4.33	-0.12	-0.08
14	Bo-474-M2	D	-12.84	-4.38	-0.08	-0.13
14	Bo-474-M2	DD	-12.82	-4.24	-0.06	0.01
15	Bo-395-M1	AA	-13.14	-4.36	0.00	0.00
15	Bo-395-M1	B	-13.11	-4.27	0.03	0.09
15	Bo-395-M1	BB	-13.18	-4.36	-0.04	0.01
15	Bo-395-M1	C	-13.14	-4.22	0.01	0.14
15	Bo-395-M1	CC	-13.11	-4.19	0.03	0.17
15	Bo-395-M1	D	-13.13	-4.28	0.01	0.08
15	Bo-395-M1	DD	-13.15	-4.31	-0.01	0.05

**Tab. 10.6. Descriptive statistics for  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  from the complete human enamel data set.**

	$\delta^{18}\text{O}$		$\delta^{13}\text{O}$	
	Statistic	Std. Error	Statistic	Std. Error
Mean	-4.3425	.06604	-13.2868	.07560
95 % Confidence Interval for Mean	Lower Bound		-13.4363	
	Upper Bound		-13.1373	
5 % Trimmed Mean	-4.3510		-13.3508	
Median	-4.3000		-13.4400	
Variance	.598		.783	
Std. Deviation	.77302		.88482	
Minimum	-6.82		-15.09	
Maximum	-2.31		-9.74	
Range	4.51		5.35	
Interquartile Range	.94		.91	
Skewness	.111	.207	1.271	.207
Kurtosis	.315	.411	2.795	.411

**Tab. 10.7. Test of normality  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  complete human enamel data set.**

	Kolmogorov-Smirnov <sup>a</sup>			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
$\delta^{18}\text{O}$	.070	137	.093	.988	137	.253
$\delta^{13}\text{C}$	.100	137	.002	.917	137	.000

a. Lilliefors Significance Correction



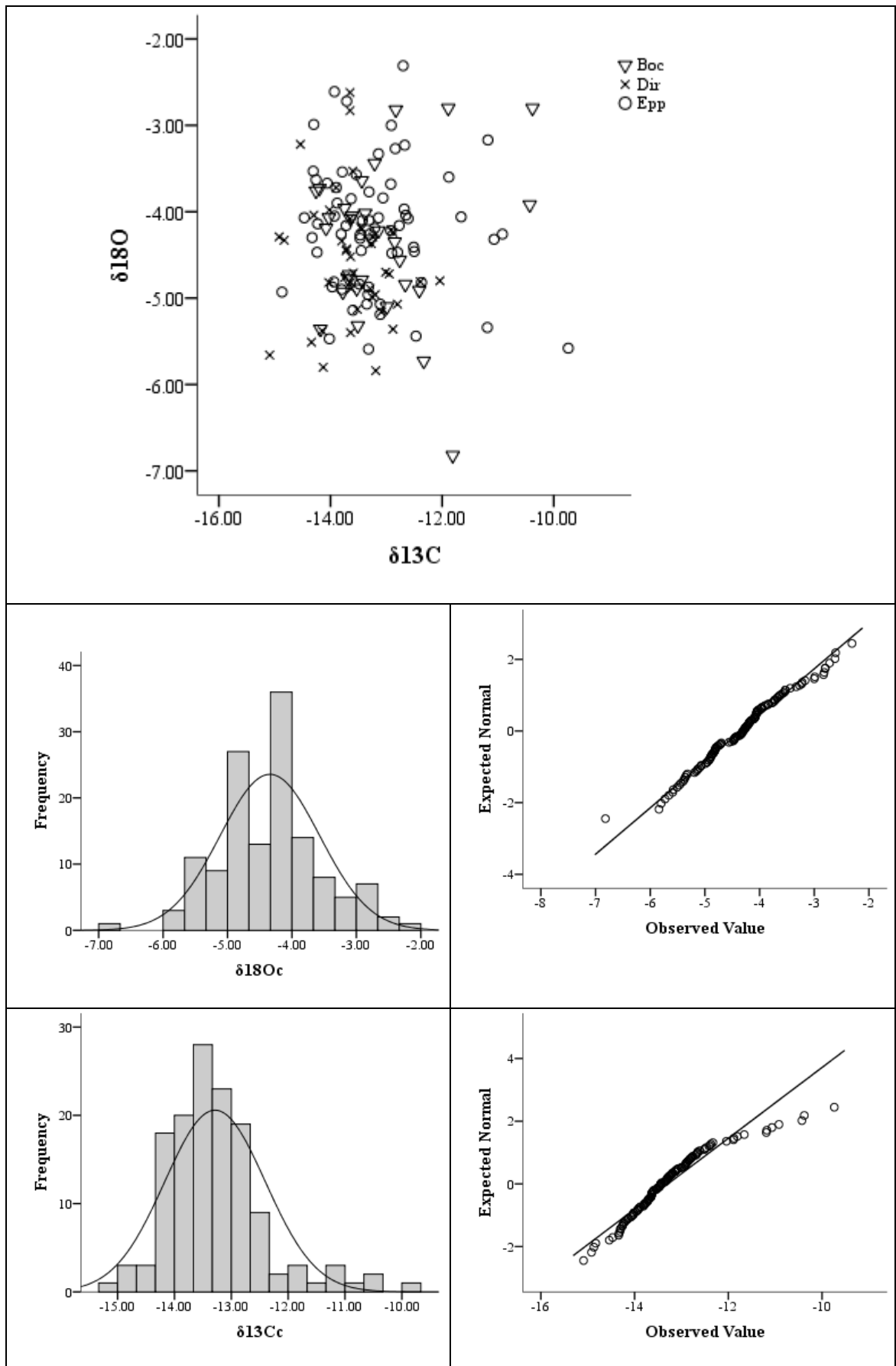


Fig. 10.7. Graphical description of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  from the complete human data set.

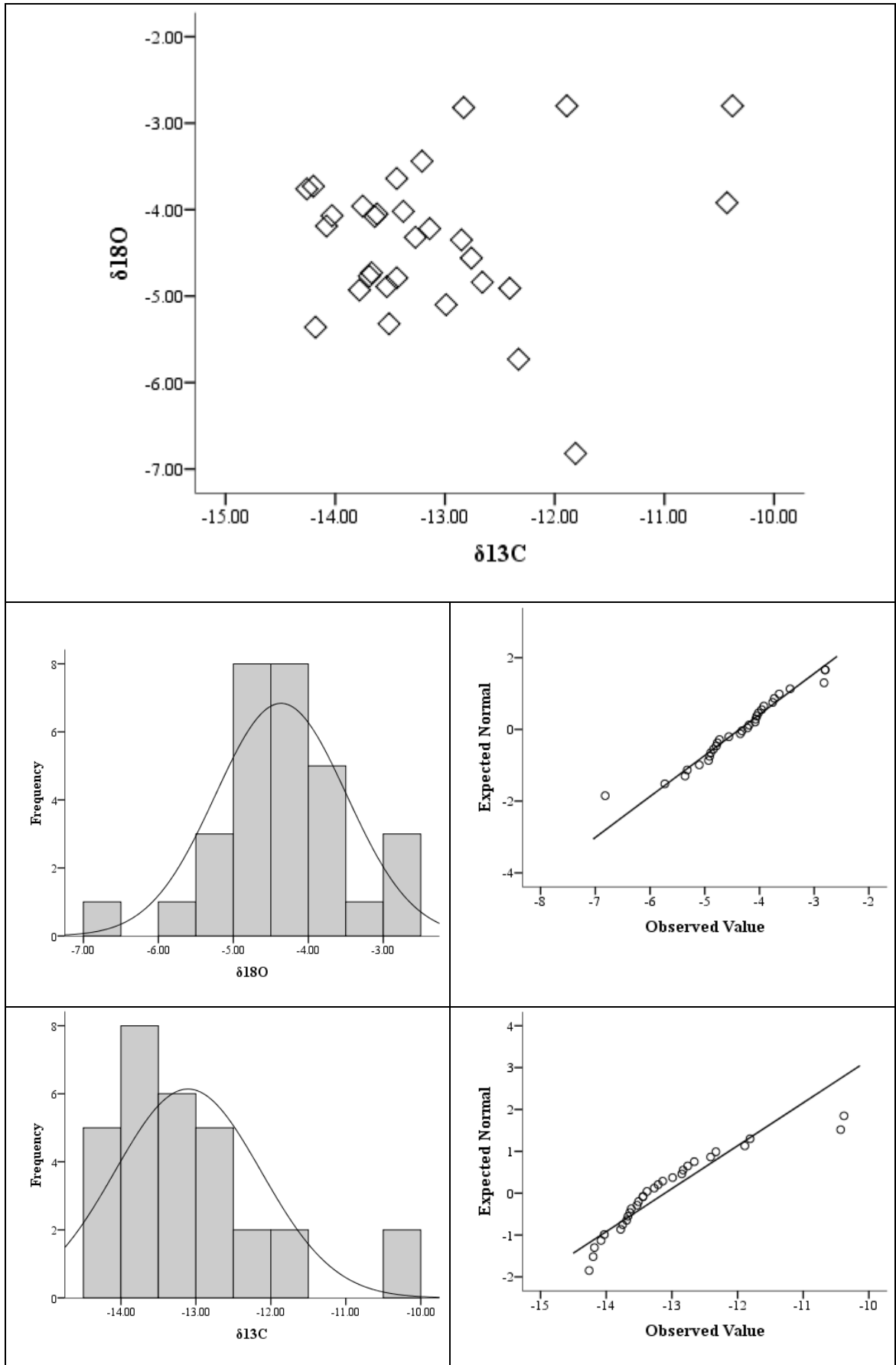


Fig. 10.8. Graphical description of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  from Bockenheim.

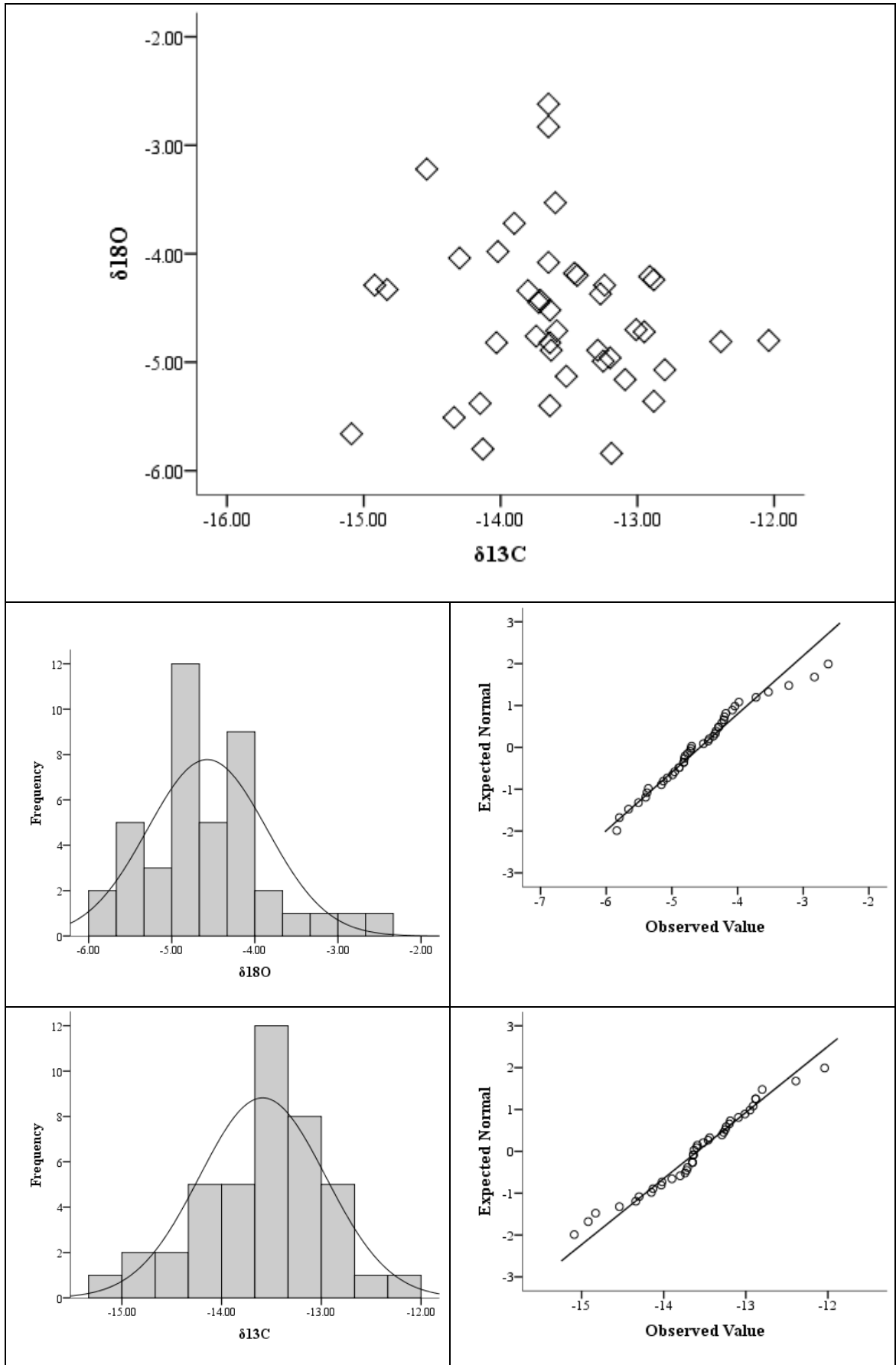


Fig. 10.9. Graphical description of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  from Dirmstein.

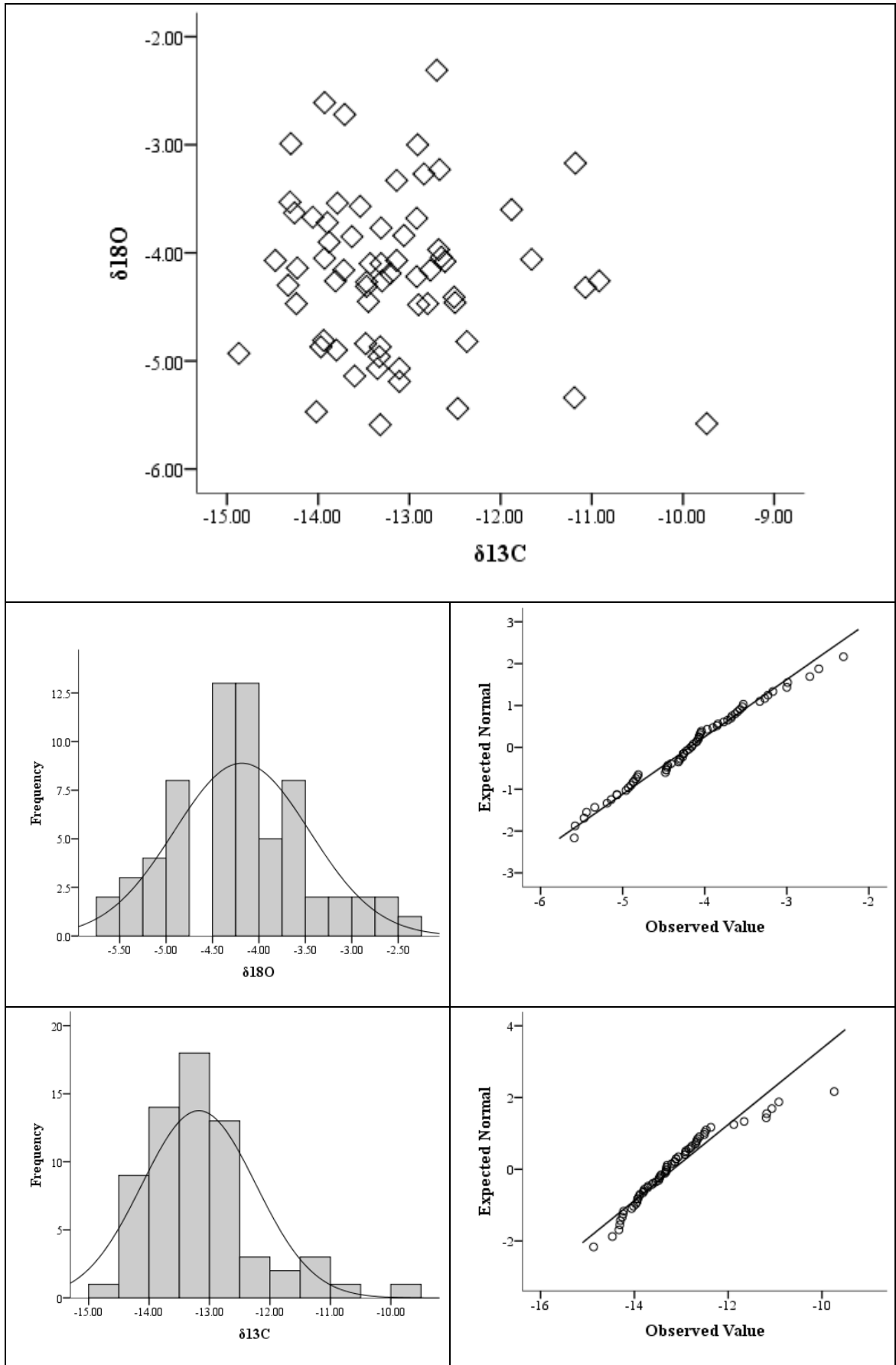


Fig. 10.10. Graphical description of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  from Eppstein.

**Tab. 10.8. Results of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  sequential cattle samples.**

Site	Grave	Tooth	Distance	$\delta^{13}\text{C}_c$	$\pm$	$\delta^{18}\text{O}_c$	$\pm$
Dir	263	M2	38	-12.06	0.01	-6.63	0.04
Dir	263	M2	35	-12.30	0.01	-6.37	0.02
Dir	263	M2	33	-12.34	0.01	-5.89	0.03
Dir	263	M2	30	-12.27	0.02	-5.12	0.04
Dir	263	M2	28	-12.06	0.01	-4.26	0.01
Dir	263	M2	24	-12.30	0.01	-4.37	0.01
Dir	263	M2	20	-12.15	0.02	-3.70	0.03
Dir	263	M2	18	-11.93	0.00	-3.60	0.02
Dir	263	M2	15	-11.92	0.02	-4.29	0.03
Dir	263	M2	13	-11.87	0.01	-5.32	0.02
Dir	263	M2	10	-11.74	0.01	-6.21	0.03
Dir	263	M2	7	-11.54	0.01	-6.36	0.02
Dir	263	M3	44	-11.93	0.01	-7.07	0.02
Dir	263	M3	41	-12.17	0.02	-7.03	0.04
Dir	263	M3	39	-12.24	0.01	-7.09	0.01
Dir	263	M3	36	-12.18	0.01	-6.44	0.01
Dir	263	M3	34	-12.23	0.01	-5.66	0.01
Dir	263	M3	32	-12.43	0.01	-5.97	0.01
Dir	263	M3	29	-12.55	0.01	-5.54	0.02
Dir	263	M3	26	-12.38	0.01	-5.30	0.03
Dir	263	M3	23	-12.42	0.02	-5.60	0.06
Dir	263	M3	20	-12.42	0.01	-6.28	0.01
Dir	263	M3	18	-12.26	0.01	-7.11	0.04
Dir	263	M3	15	-12.09	0.01	-7.81	0.02
Dir	263	M3	12	-12.13	0.00	-9.40	0.01
Dir	263	M3	9	-12.03	0.00	-8.38	0.01
Boc	181	M2	46	-	-	-	-
Boc	181	M2	44	-11.83	0.01	-5.50	0.03
Boc	181	M2	42	-11.50	0.01	-4.68	0.02
Boc	181	M2	37	-11.25	0.01	-2.94	0.01
Boc	181	M2	35	-11.07	0.00	-3.55	0.01
Boc	181	M2	33	-11.00	0.01	-3.90	0.02
Boc	181	M2	29	-10.99	0.01	-5.49	0.01
Boc	181	M2	27	-11.21	0.01	-6.16	0.02
Boc	181	M2	24	-10.99	0.03	-5.84	0.05
Boc	181	M2	21	-11.25	0.01	-7.06	0.02
Boc	181	M2	19	-11.34	0.01	-6.99	0.04
Boc	181	M2	16	-11.38	0.01	-6.95	0.02
Boc	181	M2	14	-11.32	0.01	-6.70	0.02
Boc	181	M2	11	-11.27	0.01	-6.44	0.03
Boc	181	M2	8	-11.04	0.01	-5.05	0.02
Boc	195	M3	43	-12.53	0.02	-5.84	0.05
Boc	195	M3	41	-12.12	0.01	-5.49	0.00
Boc	195	M3	38	-12.01	0.01	-5.22	0.02
Boc	195	M3	35	-11.45	0.01	-4.84	0.02

Boc	195	M3	33	-11.40	0.01	-4.88	0.02
Boc	195	M3	29	-11.30	0.00	-5.11	0.02
Boc	195	M3	27	-11.12	0.01	-4.94	0.01
Boc	195	M3	24	-11.28	0.01	-5.57	0.02
Boc	195	M3	22	-11.58	0.01	-5.69	0.01
Boc	195	M3	19	-11.92	0.01	-6.29	0.01
Boc	195	M3	15	-12.20	0.00	-6.69	0.01
Boc	195	M3	13	-12.46	0.01	-6.83	0.02
Boc	195	M3	10	-12.56	0.02	-7.09	0.04
Boc	195	M3	7	-12.41	0.01	-8.01	0.03
Boc	274	M2	23	-14.56	0.00	-5.37	0.02
Boc	274	M2	20	-14.42	0.00	-5.09	0.01
Boc	274	M2	18	-14.21	0.01	-4.19	0.01
Boc	274	M2	15	-14.07	0.01	-4.09	0.00
Boc	274	M2	12	-13.97	0.01	-4.04	0.02
Boc	274	M2	9	-13.85	0.01	-3.39	0.02
Boc	274	M2	7	-13.90	0.01	-4.47	0.03
Boc	274	M2	4	-13.92	0.01	-4.22	0.02
Boc	274	M3	30	-14.02	0.01	-6.69	0.02
Boc	274	M3	27	-13.94	0.01	-6.95	0.01
Boc	274	M3	24	-14.00	0.01	-7.57	0.01
Boc	274	M3	22	-13.97	0.00	-7.55	0.01
Boc	274	M3	19	-14.13	0.01	-7.58	0.01
Boc	274	M3	17	-14.07	0.01	-7.32	0.01
Boc	274	M3	14	-14.05	0.00	-7.14	0.01
Boc	274	M3	11	-13.89	0.01	-6.65	0.01
Boc	274	M3	9	-13.84	0.01	-6.23	0.01
Boc	274	M3	6	-13.77	0.00	-5.80	0.01
Boc	532	M2	52	-11.97	0.07	-7.94	0.21
Boc	532	M2	49	-11.69	0.11	-7.91	0.19
Boc	532	M2	45	-11.79	0.15	-7.61	0.08
Boc	532	M2	41	-11.83	0.01	-7.42	0.03
Boc	532	M2	39	-11.78	0.00	-7.19	0.02
Boc	532	M2	35	-11.77	0.08	-6.93	0.03
Boc	532	M2	32	-11.83	0.03	-6.62	0.14
Boc	532	M2	29	-11.82	0.03	-6.36	0.01
Boc	532	M2	26	-11.94	0.04	-6.26	0.06
Boc	532	M2	23	-12.02	0.02	-5.94	0.01
Boc	532	M2	19	-11.93	0.01	-5.81	0.03
Boc	532	M2	16	-11.92	0.00	-6.04	0.03
Boc	532	M2	11	-11.74	0.03	-6.19	0.08
Boc	532	M2	6	-11.26	0.00	-6.99	0.03
Boc	532	M3	60	-11.93	0.01	-6.09	0.01
Boc	532	M3	58	-11.93	0.03	-5.98	0.09
Boc	532	M3	55	-11.79	0.07	-6.00	0.09
Boc	532	M3	52	-11.69	0.01	-6.07	0.04
Boc	532	M3	48	-11.62	0.03	-6.41	0.04

Boc	532	M3	44	-11.38	0.01	-6.68	0.06
Boc	532	M3	39	-11.19	0.05	-6.98	0.13
Boc	532	M3	35	-11.13	0.07	-7.29	0.02
Boc	532	M3	30	-11.04	0.02	-7.54	0.06
Boc	532	M3	26	-11.01	0.06	-7.75	0.11
Boc	532	M3	23	-10.99	0.02	-7.57	0.08
Boc	532	M3	19	-11.20	0.07	-7.06	0.39
Boc	532	M3	14	-11.44	0.03	-7.12	0.01
Boc	532	M3	11	-11.65	0.03	-6.70	0.11

**Tab. 10.9. Trimmed  $\delta^{18}\text{O}$  data and transformation steps into  $\delta^{18}\text{O}_{\text{dw}}$  VSMOW.**

Site Grave	Tooth	$\delta^{18}\text{O}_{\text{c}}$ VPDB	A	B	C	D	E	$\delta^{18}\text{O}_{\text{c}}$ VSMOW	$\delta^{18}\text{O}_{\text{p}}$ VSMOW	$\delta^{18}\text{O}_{\text{dw}}$ VSMOW	Corr. (-0.7)
Bo459	M2	-5.7						25.0	16.1	-8.9	-9.6
Epp436	M2	-5.4	-5.4					25.3	16.4	-8.4	-9.1
Bo488	M2	-5.4	-5.4	-5.4				25.4	16.5	-8.3	-9.0
Bo470	M2	-5.3	-5.3	-5.3	-5.3			25.4	16.6	-8.2	-8.9
Epp111	M2	-5.2	-5.2	-5.2	-5.2	-5.2	-5.2	25.6	16.7	-8.0	-8.7
Bo497	P2	-5.1	-5.1	-5.1	-5.1	-5.1	-5.1	25.6	16.8	-7.9	-8.6
Epp49	M2	-5.0	-5.0	-5.0	-5.0	-5.0	-5.0	25.8	16.9	-7.6	-8.3
Epp25	M2	-4.9	-4.9	-4.9	-4.9	-4.9	-4.9	25.9	17.0	-7.5	-8.2
Dir25a	M3	-4.9	-4.9	-4.9	-4.9	-4.9	-4.9	25.9	17.0	-7.5	-8.2
Bo464	M2	-4.9	-4.9	-4.9	-4.9	-4.9	-4.9	25.9	17.0	-7.5	-8.2
Epp188	M2	-4.9	-4.9	-4.9	-4.9	-4.9	-4.9	25.9	17.0	-7.5	-8.2
Epp226	M2	-4.9	-4.9	-4.9	-4.9	-4.9	-4.9	25.9	17.0	-7.5	-8.2
Epp4C	M2	-4.8	-4.8	-4.8	-4.8	-4.8	-4.8	25.9	17.1	-7.4	-8.1
Dir43	M3	-4.8	-4.8	-4.8	-4.8	-4.8	-4.8	25.9	17.1	-7.4	-8.1
Epp208	M2	-4.8	-4.8	-4.8	-4.8	-4.8	-4.8	25.9	17.1	-7.4	-8.1
Dir24	M3	-4.8	-4.8	-4.8	-4.8	-4.8	-4.8	26.0	17.1	-7.4	-8.1
Bo382	M2	-4.8	-4.8	-4.8	-4.8	-4.8	-4.8	26.0	17.1	-7.3	-8.0
Dir26	M2	-4.8	-4.8	-4.8	-4.8	-4.8	-4.8	26.0	17.2	-7.3	-8.0
Dir26	M3	-4.7	-4.7	-4.7	-4.7	-4.7	-4.7	26.0	17.2	-7.2	-7.9
Dir24	M2	-4.7	-4.7	-4.7	-4.7	-4.7	-4.7	26.1	17.2	-7.2	-7.9
Dir25b	M3	-4.7	-4.7	-4.7	-4.7	-4.7	-4.7	26.1	17.2	-7.2	-7.9
Bo454	P2	-4.6	-4.6	-4.6	-4.6	-4.6	-4.6	26.2	17.4	-7.0	-7.7
Dir47	M2	-4.5	-4.5	-4.5	-4.5	-4.5	-4.5	26.3	17.4	-6.9	-7.6
Epp55	P2	-4.5	-4.5	-4.5	-4.5	-4.5	-4.5	26.3	17.5	-6.8	-7.5
Epp280	P2	-4.5	-4.5	-4.5	-4.5	-4.5	-4.5	26.3	17.5	-6.8	-7.5
Epp426	P2	-4.5	-4.5	-4.5	-4.5	-4.5	-4.5	26.3	17.5	-6.8	-7.5
Dir47	M3	-4.4	-4.4	-4.4	-4.4	-4.4	-4.4	26.3	17.5	-6.8	-7.5
Dir24	P2	-4.4	-4.4	-4.4	-4.4	-4.4	-4.4	26.3	17.5	-6.8	-7.5
Epp233	P2	-4.4	-4.4	-4.4	-4.4	-4.4	-4.4	26.4	17.5	-6.7	-7.4
Dir239	M3	-4.4	-4.4	-4.4	-4.4	-4.4	-4.4	26.4	17.6	-6.7	-7.4
Bo474	M2	-4.4	-4.4	-4.4	-4.4	-4.4	-4.4	26.4	17.6	-6.6	-7.3
Bo492	P2	-4.3	-4.3	-4.3	-4.3	-4.3	-4.3	26.5	17.6	-6.6	-7.3
Dir5	M3	-4.3	-4.3	-4.3	-4.3	-4.3	-4.3	26.5	17.7	-6.5	-7.2
Epp71	M2	-4.3	-4.3	-4.3	-4.3	-4.3	-4.3	26.5	17.7	-6.5	-7.2
Dir25a	P2	-4.2	-4.2	-4.2	-4.2	-4.2	-4.2	26.6	17.7	-6.4	-7.1
Dir215	M2	-4.2	-4.2	-4.2	-4.2	-4.2	-4.2	26.6	17.8	-6.3	-7.0
Epp162	M2	-4.1	-4.1	-4.1	-4.1	-4.1	-4.1	26.6	17.8	-6.3	-7.0
Epp3	M2	-4.1	-4.1	-4.1	-4.1	-4.1	-4.1	26.7	17.9	-6.2	-6.9
Bo22	M2	-4.1	-4.1	-4.1	-4.1	-4.1	-4.1	26.7	17.9	-6.2	-6.9
Epp39	M2	-4.1	-4.1	-4.1	-4.1	-4.1	-4.1	26.7	17.9	-6.2	-6.9
Dir254	M3	-4.1	-4.1	-4.1	-4.1	-4.1	-4.1	26.7	17.9	-6.2	-6.9
Epp58	P2	-4.1	-4.1	-4.1	-4.1	-4.1	-4.1	26.7	17.9	-6.2	-6.9
Bo397	P2	-4.1	-4.1	-4.1	-4.1	-4.1	-4.1	26.7	17.9	-6.1	-6.8
Epp37	M2	-4.0	-4.0	-4.0	-4.0	-4.0	-4.0	26.7	17.9	-6.1	-6.8
Bo391	M2	-4.0	-4.0	-4.0	-4.0	-4.0	-4.0	26.8	17.9	-6.1	-6.8



Bo424	M2	-3.9	-3.9	-3.9	-3.9	-3.9	-3.9	26.9	18.0	-5.9	-6.6
Epp228	M2	-3.8	-3.8	-3.8	-3.8	-3.8	-3.8	26.9	18.1	-5.8	-6.5
Epp433	M2	-3.8	-3.8	-3.8	-3.8	-3.8	-3.8	27.0	18.2	-5.7	-6.4
Bo421	P2	-3.8	-3.8	-3.8	-3.8	-3.8	-3.8	27.0	18.2	-5.7	-6.4
Dir254	M2	-3.7	-3.7	-3.7	-3.7	-3.7	-3.7	27.1	18.3	-5.6	-6.3
Epp46	M2	-3.7	-3.7	-3.7	-3.7	-3.7	-3.7	27.1	18.3	-5.6	-6.3
Epp246	M2	-3.6	-3.6	-3.6	-3.6	-3.6		27.2	18.4	-5.3	-6.0
Epp38	M2	-3.5	-3.5	-3.5	-3.5			27.3	18.5	-5.3	-6.0
Bo406	M2	-3.4	-3.4	-3.4				27.4	18.6	-5.1	-5.8
Epp198	M2	-3.2	-3.2					27.6	18.8	-4.7	-5.4
Bo392	M2	-2.8						28.0	19.2	-4.1	-4.8
Dir5	M2	-2.6						28.2	19.4	-3.8	-4.5
Epp48	M2	-2.3						28.5	19.8	-3.3	-4.0
<b>Mean</b>		-4.3	-4.4	-4.4	-4.4	-4.4	-4.4				
<b>1<math>\sigma</math></b>		0.6	0.5	0.5	0.4	0.4	0.4				
<b>Range</b>		-3.1	-3.4	-3.5	-3.5	-3.6	-3.6				
<b>2SD</b>		-5.5	-5.4	-5.4	-5.3	-5.2	-5.2				

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## **Erklärung**

Hiermit erkläre ich, Christine Jutta Schuh, geboren am 17.08.1982 in Zell (Mosel), dass diese Abhandlung nach Inhalt und Form meine eigene Arbeit ist. Beiträge von anderen als meiner Person wurden deutlich als solche hervorgehoben. Diese Arbeit wurde weder im Ganzen noch in Teilen einer anderen Stelle im Rahmen eines Prüfungsverfahrens zur Begutachtung vorgelegt, veröffentlicht oder zur Veröffentlichung eingereicht. Die Regeln guter wissenschaftlicher Praxis der Deutschen Forschungsgemeinschaft wurden bei der Entstehung dieser Arbeit eingehalten.

Kiel, den 13.01.2014