

**From marine sediments to explosive eruption record:
A case study from New Zealand and a revised methodical approach**

Dissertation

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vorgelegt von

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Erklärung

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1. ich die vorliegende Doktorarbeit selbständig, abgesehen von der Beratung durch die Betreuer, und ohne Zuhilfenahme unerlaubter Hilfsmittel erstellt habe.
2. weder diese noch eine ähnliche Arbeit an einer anderen Hochschule im Rahmen eines Prüfungsverfahrens vorgelegt, veröffentlicht oder zur Veröffentlichung vorgelegt wurde.
3. die Arbeit unter Einhaltung der Regeln guter wissenschaftlicher Praxis der Deutschen Forschungsgemeinschaft entstanden ist.
4. mir noch kein akademischer Grad entzogen wurde.

Ort, Datum

Katharina M. Pank

Preface

The extensive marine tephrochronostratigraphic study of New Zealand's volcanism based on eleven deep ocean drill sites was the main goal of my PhD project complemented by field work in New Zealand. Therefore, my supervisor Steffen Kutterolf and me planned our field campaign in spring 2020 and intended to meet with our New Zealand colleague Jenni L. Hopkins and her students for a three-week long trip at different locations on North Island in order to complement the marine tephra record and fill-in gaps in the volcanic onshore record. Preceding the field campaign we planned to attend the postcruise meeting of IODP (International Ocean Discovery Program) Exp. 375, which was scheduled in Napier, North Island (New Zealand). These postcruise meetings are a regular feature of each IODP expedition and are meant to strengthen the scientific community consisting of shipboard and shore-based scientists, to present first results and to discuss and plan future scientific output. Unfortunately, this meeting as well as the planned field work coincided with the world's first pandemic and although already in New Zealand we were forced to cancel our plans and return immediately without participating in the postcruise meeting and without doing any field work.

These circumstances also had a major effect on my PhD project. Beside the missing sample material from the onshore deposits, I was not able to integrate in the IODP Exp. 375 scientific community and therefore missed out on opportunities to establish an international scientific network, and more importantly I greatly missed out on the opportunity to discuss preliminary results and interpretations with other expedition scientists in person. Nonetheless, these circumstances brought new opportunities that allowed me to participate in other projects than originally planned - the establishments of the marine tephra records of the Aegean Sea and the Indian Ocean. Both studies gave me a broader overview about the research field of marine tephrochronostratigraphy and its applications and allowed me to collaborate with different scientists, and therefore start to establish my scientific career.

This dissertation is a cumulative work composed of four scientific articles. These articles are either published, in preparation for resubmission, or in preparation for submission to an international peer-reviewed journal. Three scientific articles present the marine tephrochronostratigraphy of New Zealand's volcanism since the Neogene (Studies I, II, III). One contribution presents a methodical approach for efficient marine tephra sampling, sample preparation and data acquisition (Study IV) with additional focus on the benefits and limitations of different coring techniques for marine tephrostratigraphy. All manuscripts are stand-alone

contributions and I am the first author of all studies. The dissertation is complemented by an introduction and scientific objectives, a conclusion and scientific outlook.

The 1st manuscript (Study I) reports on the analysed major and trace element compositions of all investigated marine volcanic samples from New Zealand recovered during different deep ocean drilling campaigns. In addition, relevant information about the drill sites, for example water and drilling depths, recovered lithostratigraphic units, and first age models, are reported here. This study provides the foundation for the 2nd (Study II) and 3rd (Study III) manuscript.

In the 2nd (Study II) and 3rd (Study III) manuscript I focus on New Zealand's marine tephrostratigraphy of the Quaternary (c. 2.6 Ma to recent) and Neogene (c. 17 Ma to 2.6 Ma). The marine tephrochronostratigraphy was established based on the marine tephra inventory and include first calculations of repose times and eruption frequencies. Study II additionally provides first holistic estimates of erupted tephra volumes and associated eruption magnitudes, whereas Study III provides first investigations of geochemical trends since the Neogene.

The 4th manuscript (Study IV) presents a methodical approach for marine tephrostratigraphy. This contribution provides a detailed description of different work steps from core to correlation and is particularly interesting for studies focussing on large sample quantities. In addition, this manuscript highlights different coring and drilling techniques in terms of their individual benefits and limitations for marine tephrostratigraphy.

During my PhD project I contributed to two other manuscripts (Woodhouse et al., 2022; Luo et al., 2023) related to my tephra studies in New Zealand by providing geochemical data, and editorial reading and writing of the manuscripts. In addition, I contributed to five other manuscripts (Kutterolf et al., 2021b; Kutterolf et al., 2021a; Kutterolf et al., 2023b; Kutterolf et al., 2023c; Kutterolf et al., 2023a) and was responsible for sample preparation and analyses, conceptualisation of the manuscripts including initial and editorial reading and writing, graphics, discussion and interpretation. Contemporaneously, I published the results of my master thesis (Pank et al., 2022) and was responsible for the sample preparation and analyses, conceptualisation of the manuscript, including initial and editorial writing, graphics, discussion and interpretation.

Abstract

The investigation of marine tephra records allows the establishment of most complete long-term eruptive sequences of volcanoes, volcanic centres, and arc systems. These eruptive sequences enable further research of systematic changes, including potential links to external forcing, over entire life cycles of volcanic systems which is a major goal of this thesis.

Five deep ocean drilling campaigns targeted the marine sediments offshore New Zealand and drilled 21 holes at eleven drill sites, covering the marine environment towards the East and Southeast of New Zealand in the direction of the prevailing winds. The recovered sediments comprised several intercalated volcanic deposits (i.e. tephra) and therefore enabled the investigation of the marine tephra record from New Zealand's volcanic arc systems. The result of this investigation is a most complete marine tephrostratigraphy of New Zealand's volcanism reaching back to the Neogene. The marine tephra record is continuous until c. 12 Ma and therefore complements and extends the volcanic onshore record of New Zealand's volcanoes, which is considered to be well-established until ≤ 61 ka. The older onshore eruptive record, however, lacks continuity most likely due to erosion or inaccessibility of volcanic deposits as discussed in several preceding onshore tephra studies. Therefore, the established marine tephrostratigraphy is of high value and a major step towards understanding and investigating New Zealand's volcanic arc systems.

Marine tephrostratigraphic studies, especially when linked to deep ocean drilling campaigns, usually imply large sample numbers, often exceeding preparation and analytical capabilities. Therefore, the tephra study of New Zealand in combination with two other very recent tephra studies, served as a case study for the establishment of a revised methodical approach.

This cumulative thesis is based on four independent manuscripts. The first three contributions present the marine tephrostratigraphy of New Zealand's volcanism reaching back to the Neogene. The fourth contribution presents a methodical approach designed for marine tephra studies and optimised for large sample quantities and can be used as a "core to correlation" - recipe. For illustration, this methodical approach particularly focusses on three marine tephra studies (New Zealand, Aegean Sea, and Sumatra/Indian Ocean) and discusses the benefits and limitations of different coring and drilling techniques for marine tephrostratigraphic studies.

The major findings of this thesis are: 1) a continuous marine tephrostratigraphy for New Zealand's volcanic arcs for the last 12 Myr that covers the lifetime of the Quaternary Taupō Volcanic Zone and parts of the Coromandel Volcanic Zone, the Neogene predecessor volcanic arc with earliest volcanism dated at c. 18 Ma, 2) temporal geochemical variations and trends

within and between the two arc systems, 3) insights into the dispersal, depositional processes and overall preservation of tephra in the marine environment, 4) first estimates of tephra volumes, equivalent magma masses and eruption magnitudes, and 5) eruption frequencies and repose times for the Quaternary and Neogene volcanic arcs.

Although the established continuous marine tephrochronostratigraphy is the most complete eruptive time series for New Zealand's volcanism up to now, only eruptions with magnitudes $M \leq 5$ were preserved as discrete layers in the marine sediments. Therefore, future tephrostratigraphic research in that area may benefit from combining the marine tephrochronostratigraphic record with preceding onshore tephra studies and ultimately result in the most complete eruptive record of New Zealand.

Kurzfassung

Die Untersuchung mariner Tephren ermöglicht die Erstellung möglichst vollständiger Langzeit-Eruptionsequenzen von Vulkanen, Vulkanzentren und vulkanischen Bogensystemen. Dies ermöglicht detaillierte Untersuchungen von systematischen Veränderungen einschließlich möglicher Verbindungen zu externen Einflüssen über den gesamten Lebenszyklus vulkanischer Systeme, was ein Hauptziel dieser Arbeit ist.

Während fünf Bohrkampagnen wurden die Tiefseesedimente vor der Küste Neuseelands untersucht und insgesamt 21 Löcher an elf Bohrlokalationen gebohrt. Sie erstreckten sich östlich und südöstlich in Richtung der vorherrschenden Winde von Neuseeland. Die gewonnenen marinen Sedimente umfassten viele zwischengelagerte vulkanische Ablagerungen (auch Tephren genannt) und ermöglichten daher die Untersuchung der marinen Tephrasequenzen der Vulkanbogensysteme Neuseelands. Das Ergebnis dieser Untersuchung ist eine äußerst vollständige marine Tephrochronostratigraphie des neuseeländischen Vulkanismus die bis ins Neogen zurückreicht. Die marine Tephra-Aufzeichnung der marinen Sedimente ist kontinuierlich bis etwa 12 Millionen Jahre und ergänzt somit die auf dem Festland vorhandene Eruptionshistorie Neuseelands. Diese ist für die letzten 61.000 Jahre sehr detailliert beschrieben und etabliert, doch wie bereits in vorherigen Tephra-Studien diskutiert, mangelt es den älteren Eruptionsaufzeichnungen an Land an Vollständigkeit, vermutlich bedingt durch Erosion oder Überlagerung der vulkanischen Ablagerungen. Daher ist die in dieser Dissertation etablierte kontinuierliche marine Tephrochronostratigraphie von großem Wert und ein wichtiger Schritt in Richtung weiterführender Erforschung der Vulkanbogensysteme Neuseelands.

Marine tephrostratigraphische Studien, insbesondere wenn sie mit marinen Bohrkampagnen in Verbindung stehen, umfassen in der Regel sehr große Probenmengen die häufig die Aufbereitungs- und Analysemöglichkeiten übersteigen. Daher diente die Erforschung der marinen Tephrostratigraphie Neuseelands in Kombination mit zwei weiteren, sehr aktuellen Tephra-Studien als Referenz für die Erstellung eines überarbeiteten methodischen Ansatzes.

Diese kumulative Dissertation basiert auf vier unabhängigen Manuskripten. Die ersten drei Beiträge präsentieren die marine Tephrochronostratigraphie des neuseeländischen Vulkanismus bis ins Neogen. Der vierte Beitrag stellt einen methodischen Ansatz vor, der für marine Tephra-Studien entwickelt und für große Probenmengen optimiert wurde. Dieser Ansatz kann als eine Art Rezept „von Kern zu Korrelation“ angewandt werden und konzentriert sich zur besseren Veranschaulichung auf drei marine Tephra-Studien (Neuseeland, Ägäisches Meer

und Sumatra/Indischer Ozean). Des Weiteren werden die Vor- und Nachteile verschiedener Kern- und Bohrtechniken für die marine Tephrostratigraphie erörtert.

Die wichtigsten Ergebnisse dieser Dissertation sind: 1) eine kontinuierliche marine Tephrostratigraphie für Neuseelands Vulkanismus der letzten 12 Millionen Jahre, welche die Lebensdauer der quartären Taupō-Vulkanzone und der jüngeren Entwicklung der neogenen Coromandel-Vulkanzone abdeckt, 2) zeitliche geochemische Variationen und Trends innerhalb und zwischen den beiden Vulkanbogensystemen, 3) Einblicke in die Verbreitung, der Ablagerungsprozesse und die allgemeine Erhaltung von Tephren im Ozean, 4) erste Abschätzungen von Tephravolumina, äquivalenten Magmamassen und Eruptionsmagnituden, und 5) Eruptionshäufigkeit und -frequenzen des quartären und neogenen Vulkanbogens.

Obwohl die in dieser Dissertation erstellte marine Tephrostratigraphie die bisher vollständigste Eruptionszeitreihe für den neuseeländischen Vulkanismus ist, ist sie teilweise unvollständig da nur die vulkanischen Ablagerungen von Eruptionen mit Magnituden $M \leq 5$ als klar identifizierbare Schichten in den Meeressedimenten erhalten sind. Zukünftige tephrostratigraphische Forschung könnte daher stark von der Kombination der hier erstellten marinen Tephrostratigraphie mit vorherigen Festland-Tephra-Studien Neuseelands profitieren und letztendlich zu einer vollständigeren Eruptionshistorie Neuseelands führen.