The effect of eclogitization of crustal rocks on the seismic properties on variable scales: Implications for geophysical imaging of eclogitization at depth

Dissertation

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Vorgelegt von:

Sascha Heinrich Pablo Zertani

Fachbereich Geowissenschaften

Freie Universität Berlin

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Gutachter:

Prof. Dr. Timm John

Prof. Dr. Frederik Tilmann

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Erklärung:

Hiermit versichere ich die vorliegende Arbeit selbständig verfasst zu haben. Es wurden keine anderen Quellen und Hilfsmittel als die in der Arbeit angegebenen verwendet und alle Ausführungen die anderen Schriften wörtlich oder sinngemäß entnommen wurden sind kenntlich gemacht. Die Arbeit lag bisher weder in gleicher noch in ähnlicher Form einer Prüfungsbehörde vor.

Berlin, 2019

"Geologists have a saying – rocks remember."

Neil Armstrong

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Summary

Plate tectonics shapes the face of the earth and subduction and collision zones are among the most important features on Earth. Here, crustal material is recycled into the mantle or integrated into growing orogens. However, the processes active at depth cannot be studied directly and we thus rely on geophysical imaging methods to visualize the geometries that result from the ongoing processes. Additionally, these processes can be studied in fossil subduction and collision zones. However, the scales at which observations from geophysical imaging are made are orders of magnitude larger than those made in field-based studies of fossil subduction and collision zones.

This thesis provides insight into how eclogitization modifies the physical properties of deeply buried rocks and what influence the resulting lithologies and their geometrical configuration have on geophysical imaging. In an interdisciplinary approach, I show how structures that are likely representative for those present at depth in subduction and collision zones develop and what their geometries at depth will be. I then derive their petrophysical properties and show how these are modified on various scales, and how this influences the detectability of such associations using geophysical imaging techniques.

To do so, the island of Holsnøy in western Norway serves as a natural laboratory that is ideal to study eclogitization of crustal material. Geological mapping on Holsnøy constrains the geometric framework of the constituting lithologies and the scales at which such structures could be expected to establish. Previously, several authors have shown that many of the eclogite occurrences on Holsnøy are produced contemporaneously with ductile deformation forming shear zones at various scales. Our geological mapping aided by photogrammetry using drone images reveals that large parts of this exposed continental sliver were eclogitized statically without associated ductile deformation. This shows that even in domains with ongoing regional deformation, low-strain domains develop within the descending crustal material.

Nevertheless, even the major shear zones that are exposed are only a few hundred meters thick, and thus far below the scale that is detectable by geophysical imaging techniques. However, geological mapping of the area suggests that the exposed structures are, at least in a qualitative sense, scale independent, suggesting that the same structural framework could be present at a larger scale in active subduction and collision zones.

Measurements of P and S wave velocities of the exposed granulitic protolith and eclogites suggest that eclogitization of the lower crust causes three major changes of the petrophysical properties: (1) increased P and S wave velocities, (2) an increase of the seismic anisotropy, and (3) a decrease of the V_P/V_S ratio, suggesting distinct variations in the geophysical signal when the descending material is partially eclogitized. Additionally, testing the signal that the exposed shear zones would give in reflection seismic and receiver function studies reveals that the variations in shear zone structure indeed produces variations in the retrieved waveforms.

Nevertheless, as the exposed structures are too small for geophysical imaging, the finite element method is used to calculate the effective properties of representative structures acting as an effective medium. The results show that the geometrical configuration of the constituting lithologies only has a minor impact on the P wave velocities and anisotropies of the resulting effective medium. Furthermore, our effective medium calculations on the kilometer scale show that eclogitization of crustal material can indeed produce significant seismic anisotropy. In this case, the calculated anisotropy reaches ~5%, which would produce a dependence of the retrieved signal in, for example, receiver function studies on the backazimuth of the sampled rays. Such backazimuthal dependence is indeed observed in active collision zones such as the Himalaya-Tibet collision system and the results presented here can thus be used to constrain the lithologies at depth, suggesting that the lower crust of India below the Himalaya is partially eclogitized along shear zones similar to those exposed on Holsnøy.

Zusammenfassung

Plattentektonik formt die Erdoberfläche und Subduktions- und Kollisionszonen gehören zu den wichtigsten Merkmalen der Erde. Hier wird Krustenmaterial in den Mantel zurückgeführt oder in wachsende Orogene integriert. Diese in großen Tiefen stattfindenden Prozesse können jedoch nicht direkt untersucht werden, weshalb wir auf geophysikalische Bildgebungsmethoden zurückgreifen müssen um die Geometrien zu visualisieren, die sich aus den laufenden Prozessen ergeben. Zusätzlich können diese Prozesse im Gelände an fossilen Subduktions- und Kollisionszonen untersucht werden. Allerdings untersuchen geophysikalische Methoden die zugrundeliegenden Prozesse auf ganz anderen Maßstäben als dies in Gelände basierten Studien gemacht werden kann.

Diese Arbeit gibt einen Einblick, wie Eklogitisierung die Eigenschaften von tief versenktem Material verändert und welchen Einfluss die resultierenden Lithologien und ihre geometrische Konfiguration auf die geophysikalischen Abbildungen von aktiven Kollisionszonen haben. Mit einem interdisziplinären Ansatz zeige ich, wie sich die Strukturen entwickeln, die repräsentativ sind für die sich in der Tiefe in Subduktions- und Kollisionszonen befindenden, und wie ihre Geometrien in der Tiefe aussehen könnten. Ich bestimme dann ihre petrophysikalischen Eigenschaften und zeige, wie diese in verschiedenen Maßstäben modifiziert werden. Außerdem untersuche ich den Einfluss dieser Strukturen auf geophysikalische Methoden und inwiefern die Strukturen in der Tiefe abbildbar sind.

Zu diesem Zweck dient die Insel Holsnøy in Westnorwegen als natürliches Labor, in dem die Eklogitisierung von krustalen Gesteinen untersucht werden kann. Geologische Kartierung auf Holsnøy zeigt das geometrische Gerüst der anstehenden Lithologien und in welchen Maßstäben sie entstehen könnten. Mehrere Studien haben bereits gezeigt, dass viele der Eklogitvorkommen auf Holsnøy unter dem Einfluss von duktiler Verformung entstanden sind und sich dabei Scherzonen in verschiedenen Maßstäben bildeten. Unsere neue geologische Karte, die durch Photogrammetrie unter der Verwendung von Drohnenbildern unterstützt wird, zeigt, dass große Teile dieses Stückes kontinentaler Kruste statisch, ohne damit verbundene duktile Verformung, eklogitisiert wurden. Dies zeigt, dass auch unter dem Einfluss regionaler Verformung Bereiche innerhalb der eklogitisierenden Kruste weitestgehend unverformt bleiben.

Die Hauptscherzonen in diesem Gebiet sind nur wenige hundert Meter dick und damit weit kleiner als die mögliche Auflösung von geophysikalischen Methoden. Die geologische Kartierung des Gebiets legt jedoch nahe, dass die exponierten Strukturen zumindest in qualitativer Hinsicht maßstabsunabhängig sind, was darauf hindeutet, dass derselbe strukturelle Aufbau in aktiven Subduktions- und Kollisionszonen in größerem Maßstab vorhanden sein könnte.

Messungen der P und S Wellengeschwindigkeiten der anstehenden Granulite und Eklogite legen nahe, dass die Eklogitisierung der unteren Kruste drei wesentliche Änderungen der petrophysikalischen Eigenschaften verursacht: (1) erhöhte P und S Wellengeschwindigkeiten, (2) eine Zunahme der seismischen Anisotropie

und (3) eine Abnahme des V_P/V_S Verhältnisses. Eklogitisierung bewirkt also charakteristische Änderungen des geophysikalischen Signals. Zusätzlich zeigen Untersuchungen des erwartenden Signals, welches die vereinfachten Scherzonen in seismischen Reflexionsseismischen und Receiver Function Studien verursachen würden, dass die Variationen in der Scherzonenstruktur tatsächlich Variationen in den geophysikalischen Ergebnissen erzeugen.

Da die exponierten Strukturen für die geophysikalische Abbildung jedoch zu klein sind, werden mit der Finite-Elemente-Methode die effektiven Eigenschaften repräsentativer Strukturen berechnet, die als effektives Medium wirken. Die Ergebnisse zeigen, dass die geometrische Konfiguration der Lithologien nur einen geringen Einfluss auf die P Wellen Geschwindigkeiten und Anisotropien des resultierenden effektiven Mediums hat. Darüber hinaus zeigen unsere Berechnungen für effektive Medien im Kilometerbereich, dass die Eklogitisierung von Krustenmaterial tatsächlich eine signifikante seismische Anisotropie hervorrufen kann. In diesem Fall erreicht die berechnete Anisotropie ~5%, was beispielsweise bei Receiver Functions Studien zu einer Abhängigkeit des abgerufenen Signals vom Rückazimuth führen würde. Eine solche Abhängigkeit vom Rückazimuth wird in der Tat in aktiven Kollisionszonen wie dem Himalaya-Tibet-Kollisionssystem beobachtet. Die hier vorgestellten Ergebnisse können daher verwendet werden, um die Lithologien in der Tiefe zu charakterisieren und weisen darauf hin, dass die indische Unterkruste ähnlich aufgebaut sein könnte wie das fossile Beispiel aus Holsnøy.

Chapter 1

Introduction

1.1 Seismic imaging of eclogitization at depth

Subduction and collision zones are the main site on Earth where crustal material is recycled back into the mantle or integrated into growing orogens. These processes occur on spatial and temporal scales so large that direct observation is difficult. Additionally, these processes occur at depths that are inaccessible for direct probing. Thus, we rely on geophysical methods to unravel the active processes and the resulting geometries that are accommodated in subduction and collision settings. A wide variety of seismological studies provides information that helps to understand how these processes progress and how they shape subduction and collision zones.

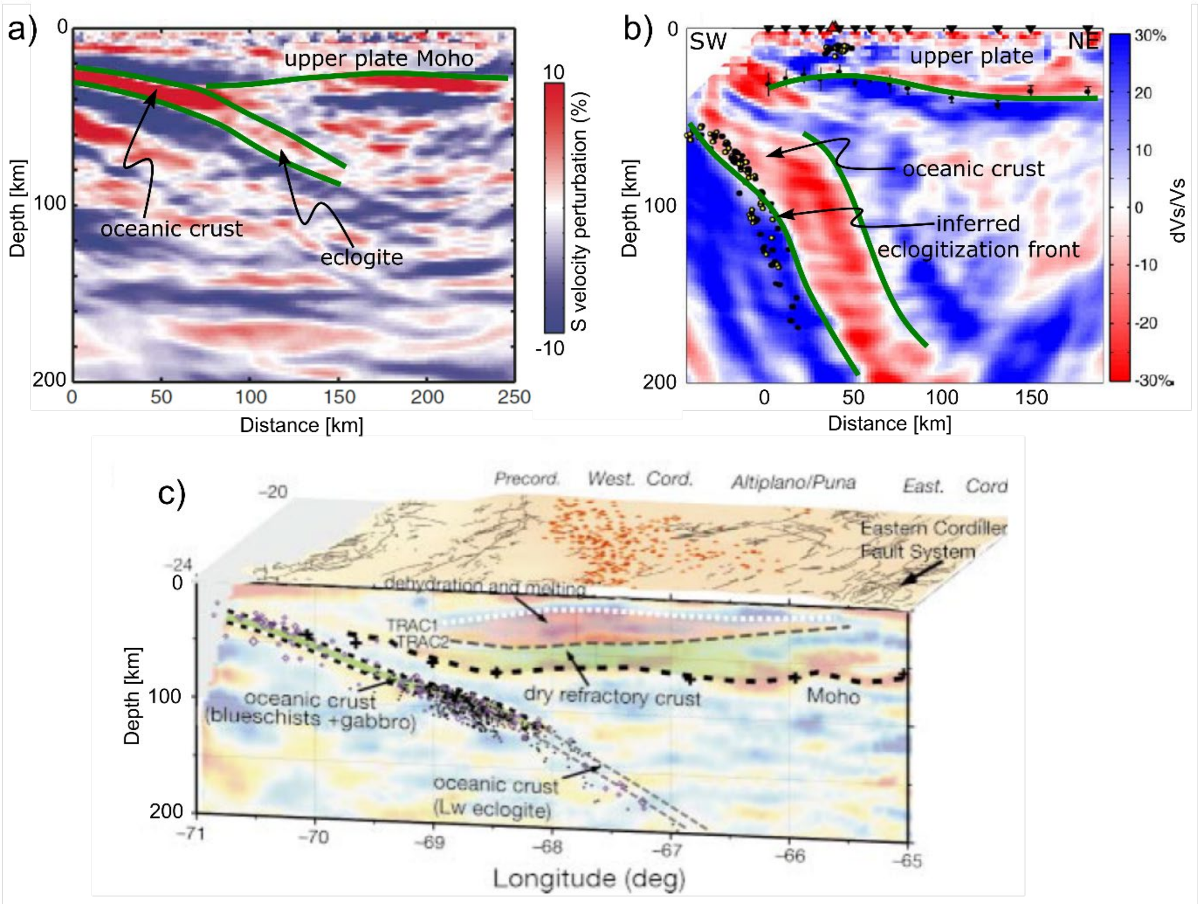

Figure 1.1. Examples of geophysical studies that target subduction zones. (a) Cascadia subduction zone showing steepening of the subducting oceanic crust after eclogitization (modified from Rondenay et al., 2008). (b) Receiver function image showing the subduction of the Cocos plate below Central America. The eclogitization front is inferred based on a change in the nature of the discontinuity (modified from MacKenzie et al., 2010). (c) Interpreted receiver function image of the subducting plate below the Andes, suggesting kinetically delayed eclogitization of the subducting crust (Yuan. et al., 2000)

Specifically, the receiver function method is often utilized to image subduction and collision zones (e.g., Rondenay et al., 2008; Schulte-Pelkum et al., 2005; Yuan et al., 2000). It is based on the conversion of teleseismic waves at boundaries of contrasting impedance and takes advantage of the conversion of P to S waves and vice versa. This conversion results in a difference in the arrival times of the primary and converted waves, which is used to calculate the depth of the boundary at which the conversion took place. Consequently, the receiver function method illuminates boundaries with contrasting impedance, that could be caused by structural features such as shear zones or by large-scale lithologic layering. The main feature in subduction and collision zones that is typically imaged by the receiver function method is the Mohorovičić discontinuity (Moho; e.g., MacKenzie et al., 2010; Nabelek et al., 2009; Yuan et al., 2000), as it is marked by a sharp decrease of the seismic velocities from the mantle into the crust therefore making it the most prominent feature (e.g., Bostock, 2013).

Additionally, imaging of crustal material that is deeply buried or subducted reveals several features in need of interpretation (Fig. 1.1). Typically, the descending crust can be imaged clearly at shallow levels and the seismic signal progressively weakens in the deeper parts (Figs. 1.1 and 1.2; Pearce et al., 2012; Schneider et al., 2013; Yuan et al., 2000). This weakening is usually attributed to eclogitization and subsequent densification of the crustal material that leads to a weakening of the impedance contrast compared to the adjacent mantle (e.g., Hetényi et al., 2007; Rondenay et al., 2008). After eclogitization is complete the seismic properties of the mantle and the crust are essentially the same and eclogites at depth are thus considered to be seismically invisible.

This zone of weakening of the seismic signal is of particular interest in many studies as it can reveal ongoing processes at depth and possibly show how the descending material is modified both structurally as well as petrologically. Below the Central Andes, for example, receiver function studies on P to S converted teleseismic waves have shown that the Moho and subsequently the subducting oceanic crust of the Nazca plate can be imaged to a depth of ~120 km, after which it becomes invisible (Yuan et al., 2000). These observations indicate that the gabbro-to-eclogite metamorphic reaction is kinetically delayed, as thermodynamic considerations would suggest that the transformation must occur within a shallower part of the subduction zone.

Similarly, receiver function studies from the Pamir image what is interpreted to be subduction of continental crust. Here, the strength of the receiver signal starts to decrease at a depth of ~100 km but only disappears entirely below ~150 km (Fig. 1.2a; Schneider et al., 2013). The study concludes that this progressive weakening of the receiver function signal is caused by ongoing eclogitization of subducting lower continental crust, and that the transformation to eclogite is only complete below ~150 km. Thus, the results infer that the weakening or "blurring" of the receiver function signal could be indicative of ongoing eclogitization in active subduction and collision settings.

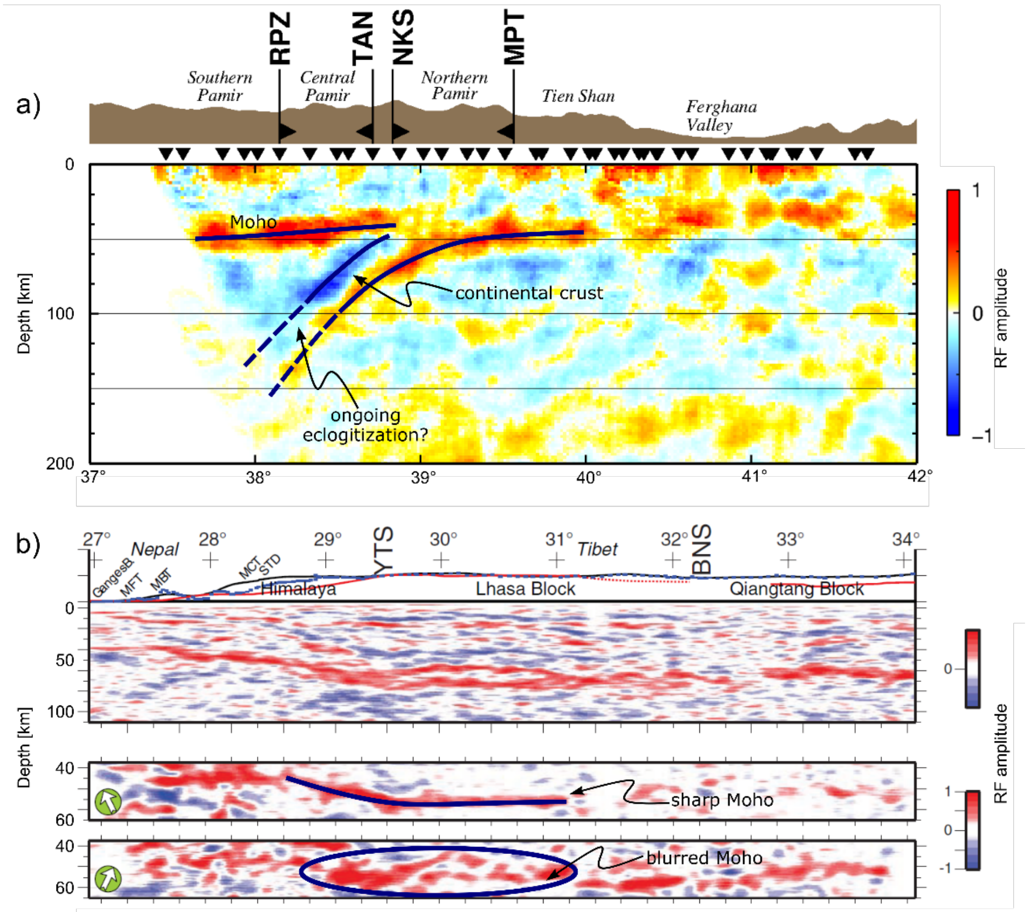

Figure. 1.2. Examples of the features detected by receiver function studies. (a) Receiver function image visualizing the downgoing Eurasian crust beneath the Pamir, showing a clear signal in the shallow part down to ~100 km and a weakening of the signal in the lower part that is interpreted to be caused by ongoing eclogitization of the crust (modified from Schneider et al., 2013). (b) Receiver function images of the Indian crust below the Himalaya. The image shows the difference between the retrieved signal using incoming waves from the north (middle) and the south (bottom), that lead to the interpretation that the Indian lower crust has a northward dipping anisotropic fabric (modified from Nabelek et al., 2009).

Furthermore, Nabelek et al. (2009) report results utilizing the receiver function method below the Himalaya, where the lower crust of the Indian plate is visualized below the Asian plate. Here, a density increase of the subducting material has been shown that is interpreted to be coeval with eclogitization of the crustal material (Hetényi et al., 2007). However, utilizing waves from different backazimuths gives distinctly different receiver function results (Fig. 1.2b). More specifically, Nabelek et al. (2009) report that the Moho is sharp when illuminated by incoming waves from the north, but appears blurred using incoming waves from the south (Fig. 1.2b). This suggests that the lower Indian continental crust below the Himalaya has an internal anisotropic fabric. As P waves are only converted to S waves if they meet the boundary at an oblique angle, the anisotropic fabric must be oriented perpendicular to the incoming waves from the south and the fabric must therefore be dipping toward the north. Similarly, Schulte-Pelkum et al. (2005) propose a north dipping anisotropic fabric within the Indian crust, which is also based on a backazimuthal dependence of the retrieved receiver function signal.

While these examples suggest ongoing processes potentially modifying the descending material based on the retrieved signal, geophysical studies can provide information for ongoing subduction zone processes even at greater depths. For example, the zone of eclogitization is often associated with a steepening of the Wadati-Benioff zone suggesting a kink in the geometry of the subducting slab (e.g., Rondenay et al., 2008; Yuan et al., 2000). Possibly, this is caused by the densification of the crustal material during eclogitization and a subsequent change in the buoyancy forces acting on the subducting material, i.e., an increase of slab pull (Klemd et al., 2011).

Thus, seismological studies, and receiver function studies in particular, provide information on many aspects of the processes going on during active subduction and collision. They are, however, restricted by the resolution that can be achieved and their interpretation is reliant on information from surface exposures to identify the ongoing processes. The wavelengths that can be sampled to image the structures at depth are on the kilometer-scale and the structures that can be resolved with such methods are thus also on the kilometer-scale. The resolution is further strongly dependent on the density of the station network during data acquisition. In order to study smaller-scale features, such as the internal structure of the subducted or buried crust at depth, it is necessary to study exposures of fossil subduction and collision zones that expose material that has been transformed at depth and then exhumed, and compare these examples with the ones obtained from active subduction and collision zones.

1.2 Eclogitization from a field perspective

Eclogites are present in many HP metamorphic belts and they are essential for our understanding of geodynamic processes as they can record the pressure-temperature-time (P-T-t) paths during burial and exhumation of crustal rocks. Eclogites, in the strictest sense, form during subduction and subsequent eclogite-facies metamorphism of mafic crust, i.e., oceanic crust, by the dehydration of blueschists (e.g., John et al., 2008; Peacock, 1990). However, in a geodynamic context it is important to also regard other eclogite-facies rocks that have formed from, for example, the sedimentary cover of oceanic crust or continental crust, as they can also record P-T-t paths and provide knowledge of the ongoing processes at depth in collision and subduction zones.

In the field, eclogites and related eclogite-facies rocks are often exposed as lenses or boudins, along shear zones, or in unregular or patchy structures (e.g., Austrheim, 1987; Austrheim, 1991; John & Schenk, 2003; Pleuger et al., 2003). Full crustal sections of eclogites are typically not exhumed, possibly because the transformation to eclogite decreases the buoyancy of the crustal material, which could provide a natural hinderance for the exhumation of completely eclogitized crustal sections (Klemd et al., 2011). Alternatively, some exposures of eclogites might be caused by tectonic overpressure exploiting pre-existing lithological inhomogeneities, implying that the rocks reached depths where eclogite-facies P-T conditions would be expected (Jamtveit et al., 2018). Additionally, structures and mineral assemblages are often overprinted during exhumation and the exposed eclogites might only be remnants of larger scale eclogitization at depth (e.g., Pleuger et al., 2003).

Specifically, eclogitization of continental crust seems enigmatic, as continental crust should be too buoyant to subduct to depths where eclogite-facies P-T conditions prevail. Nevertheless, many studies provide evidence that continental crust can indeed be buried to those depths and reequilibrate at eclogite-facies P-T conditions (e.g., Austrheim, 1998; Engi et al., 2018; Wain et al., 2001).

Contrary to a typical prograde metamorphic evolution of oceanic crust, where dehydration of blueschists causes the formation of an eclogite mineral assemblage, continental crustal rocks are often dry. In this case, the crustal rocks often escape petrological modification even at great depths due to sluggish kinetics. Then, the introduction of an external fluid is often necessary to trigger metamorphic reactions (e.g., Jackson et al., 2004). While some studies report eclogitization of dry rocks without the addition of an external fluid (e.g., Hawemann et al., 2019; Menegon et al., 2017), the majority of studies shows that eclogitization is often facilitated by fluid infiltration (e.g., Austrheim, 1987; Beinlich et al., 2010; John & Schenk, 2003). Thus, eclogitization is often triggered along structural precursors (Austrheim, 1987), along veins (Beinlich et al., 2010), or by dissolution-precipitation reactions (John & Schenk, 2003).

1.3 Holsnøy as an example for the eclogitization of dry crust

The rocks exposed on the island of Holsnøy belong to the Lindås nappe, which is part of the Bergen Arcs. The Bergen Arcs are a series of arcuate nappes centered around the city of Bergen in western Norway. The Lindås nappe originates from the hyperextended continental margin of Baltica and is associated with the Jotun and Dalsfjord nappes (Jakob et al., 2019). Together, these nappes were previously part of the Jotun microcontinent that was located at the distal part of the hyperextend margin before the Caledonian collision (Jakob et al., 2019).

The Lindås nappe was then introduced into the collision zone as the leading edge of Baltica and reequilibrated at eclogite and amphibolite-facies P-T conditions. The main eclogite occurrences are exposed on the island of Holsnøy today and are characterized by significant hydration. Fluids were introduced into the rock volume along brittle fractures facilitating mineral reactions (Austrheim, 1987). Brittle fracturing at eclogite-facies conditions is evidenced by pseudotachylytes that show eclogite-facies assemblages (Austrheim & Boundy, 1994) and by fracturing and subsequent healing of garnets (Raimbourg et al., 2007). Eclogitization then proceeded along shear zones and in patches of static reequilibration (e.g., Austrheim, 1987; Boundy et al., 1992; Raimbourg et al., 2005).

It is well established that the eclogite shear zones on Holsnøy widen progressively through time and connect into shear zone networks (Jolivet et al., 2005). This way, shear zones that are only a few centimeters thick develop into shear zones with a width of more than 100 m (Boundy et al., 1992; Raimbourg et al., 2005). Essentially, this lead to the formation of a shear zone network on the kilometer scale that is exposed on Holsnøy today and the shear zones surround relict granulite blocks that survived eclogitization unaltered (Austrheim, 1987).

Additionally, the rocks on the island of Holsnøy have also been overprinted by amphibolite-facies metamorphism (Centrella, 2019). The relationship of the timing of amphibolite and eclogite-facies metamorphism has recently been a matter of debate. Eclogite-facies metamorphism has been dated to have occurred at ~429 Ma (Glodny et al., 2008). Amphibolite-facies metamorphism, on the other hand, has been previously thought to have occurred later at ~414 Ma (Glodny et al., 2008). However, recent dating suggests that amphibolite-facies metamorphism might have already occurred shortly after peak eclogite-facies conditions (Jamtveit et al., 2018). In any case, the amphibolite-facies overprint proceeded very similarly to the eclogite-facies overprint, mainly forming along shear zones but also as patches of static alteration.

1.4 Petrophysical properties of the lower crust and eclogites

The petrophysical properties of natural rocks are essentially controlled by their mineral assemblage (e.g., Hacker et al., 2003). However, crystallographic preferred orientations, shape preferred orientations, and the distribution of minerals throughout the rock volume can significantly modify P and S wave velocities and can produce a directional dependence of the wave speeds, i.e., seismic anisotropy (e.g., Bascou et al., 2001; Faccenda et al., 2019; Keppler et al., 2017; Kern & Fakhimi, 1975; Kern et al., 1997).

A variety of methods are utilized to calculate or measure these properties. P and S wave velocities can be calculated based on the mineral abundance of the rocks (e.g., Abers & Hacker, 2016) and/or based on thermodynamic considerations (e.g., Hacker et al., 2003). This, however, usually only provides isotropic velocities without any information on the directional dependence of wave speeds. Alternatively, anisotropic seismic properties can be calculated based on crystallographic preferred orientations of the mineral phases (Mainprice & Humbert, 1994). While the latter is often performed on the thin section scale (e.g., Keppler et al., 2017), seismic velocities can also be measured using ultrasonic pulse laboratory techniques on larger samples (centimeter scale; Kern et al., 1996). Here, the velocities can be measured in various directions of the rock volume, thus providing information on seismic anisotropy, and while varying pressure and temperature conditions (e.g., Almqvist et al., 2013; Kern & Fakhimi, 1975).

The lower continental crust is composed of amphibolite to granulite-facies rocks with variable compositions. P and S wave velocities can thus vary significantly. Depending on the composition, P wave velocities can range from ~6.0 to ~7.5 km s^{-1} and S wave velocities can range from ~3.4 to ~4.2 km s^{-1} (Weiss et al., 1999). In a study dealing with an exposed transition from continental crust to mantle rocks, Brown et al. (2009) obtained P and S wave velocities for felsic gneisses and intermediate granulites of ~6.6 km s^{-1} (P wave) and 3.9 km s^{-1} (S wave) and for mafic granulites of 7.3 km s^{-1} (P wave) and 4.2 km s^{-1} (S wave). In a global compilation Christensen and Mooney (1995) summarize that the average crustal P wave velocity at depths between 25 and 35 km ranges from ~6.6 to 7.1 km s^{-1}. In terms of seismology, a general upper limit can be given to lower crustal velocities by the definition of the Moho, that states that P wave velocities of >7.6 km s^{-1} indicate a transition into the mantle (Jarchow & Thompson, 1989).

As the composition of the lower crustal rocks varies significantly, the seismic anisotropy is also distinctly different for the various rock types. For example, Weiss et al. (1999) report a P wave anisotropy of ~9% for a biotite-plagioclase gneiss, whereas the same study gives a P wave anisotropy of ~2% for a sillimanite-garnet gneiss. Both of the reported lithologies are from the same lower crustal section in Southern Calabria. P wave anisotropy of various lithologies of an exposed crust-mantle boundary in Cabo Ortegal (Spain), however, are reported to be very uniform at ~5–6% (Brown et al., 2009), which is within the typically reported range of lower crustal rocks and granulites (e.g., Fountain et al., 1994; Lloyd et al., 2011).

Eclogites are typically considered to have high seismic velocities. For example, P and S wave velocities of eclogites reported from the Bohemian massive average ~8.1 km s^{-1} and 4.3 km s^{-1}, respectively (Babuška et al., 1978). Based on electron backscatter diffraction (EBSD) measurements and the subsequent calculation of seismic velocities Bascou et al. (2001) obtain average P and S wave velocities for eclogites of 8.6 and 4.9 km s^{-1}. Thus, eclogite velocities are essentially the same as mantle velocities and eclogites are thus considered to be seismically invisible (e.g., Worthington et al., 2013). Seismic anisotropy of eclogites, however, is typically thought to be low (Babuška et al., 1978). Depending on the composition, typical values range from 3–6% P wave anisotropy (Bascou et al., 2001; Manghnani et al., 1974; Mauler et al., 2000) and only few studies report P wave anisotropy measurements up to 8% (e.g., Kern et al., 1996).

1.5 The SPP "Mountain building in 4 dimensions"

The priority program "Mountain Building in Four Dimensions" (MB-4D) is a collaborative and interdisciplinary project involving various German universities and research institutes. It is part of the international AlpArray mission, which is a large international collaborative effort to image the structure of the Alps from the surface to the deep mantle using a variety of geophysical methods. Within this framework, MB-4D contributes to the understanding of the geology of the Alps integrating various approaches. To achieve this, the priority program is divided into four themes:

(1) Reorganization of the lithosphere during mountain building,

(2) Surface response to changes in mountain structure on different time scales,

(3) Deformation of the crust and mantle during mountain building,

(4) Motion patterns & seismicity.

In this context, this thesis is part of the project "Understanding subduction by linking surface exposures of subducted and exhumed crust to geophysical images of slabs" that is a collaborative effort between the Freie

Universität Berlin, the GeoForschungsZentrum Potsdam, and the Johannes-Gutenberg-Universität Mainz. The project is divided into three work packages:

(1) Kinematic and thermobarometric evolution of subducting continental crust,

(2) Seismic properties of crystalline continental crustal (U)HP rocks,

(3) Imaging of the subducting crust and crustal structure.

Within (2) this thesis provides first-hand information on geometries representative for metamorphism in convergent settings and the resulting petrophysical properties of the rocks, as well as the detectability of such structures at depth.

1.6 Aim of the thesis

This thesis presents cumulative research that has the aim to significantly improve our understanding of how eclogitization of continental crust influences the petrophysical properties of the constituting rocks and how this influences geophysical imaging on a large scale. To do so, the thesis combines field-based constraints on the structures that are established during the eclogitization process and the geometrical relationship of the lithologies. The seismic properties of the rocks are derived from laboratory measurements and thermodynamic calculations are performed on the base of samples that were collected while considering their structural relationship in the field. The information derived from this approach is integrated into simplified feasibility tests considering the resolution of geophysical imaging to asses which structures would be visible in seismological methods and how the structures affect the signal that could potentially be retrieved at active subduction and collision zones. For a coherent picture of the effect of partial eclogitization of crustal material including the associated geometric configuration, one field example of partially eclogitized lower continental crust on Holsnøy (western Norway) was chosen, that serves as a guide throughout the research presented in this thesis.

1.7 Outline of the thesis

This dissertation is a cumulative effort and is made up of three main chapters, that target different aspects of the effect that eclogitization has on the properties of crustal rocks. Additionally, conference contributions and coauthored manuscripts that are related to this thesis are listed in Appendix A.

Chapter 2 (published in *Tectonics*, 2019)

This chapter characterizes the structures of a continental sliver which underwent partial eclogitization. It presents a new geological map of the central part of the island of Holsnøy, focusing on the structural associations that were produced by partial eclogitization. Classical field mapping was supported by 3D photogrammetry using drone images.

Timm John and Sascha Zertani designed the project. Sascha Zertani conducted the field work and mapped the area, with help from Loic Labrousse, Timm John, and Torgeir B. Andersen. Sascha Zertani digitized the resulting map, combined the gathered field data, and interpreted the results. Torgeir B. Andersen provided the drone and assisted Sascha Zertani with analysis of the obtained images. Sascha Zertani interpreted the images with help of Loic Labrousse. Piloting of the drone by Hans Jørgen Kjøll is greatly acknowledged. All authors were involved in discussions shaping the interpretation. Sascha Zertani wrote the manuscript with all authors commenting on various versions of the manuscript.

Chapter 3 (published in *Journal of Geophysical Research: Solid Earth*, 2019)

This chapter presents a multi-methodological approach to constrain the petrophysical properties of both the lower crustal granulites, as well as the eclogites. Laboratory measurements are used to constrain anisotropic P and S wave velocities, which are combined with isotropic velocities from thermodynamic calculations. The results are compared to rock textures obtained via neutron diffraction measurements. The results are combined into simplified shear zone models that are then used to calculate the expected seismic response.

Timm John, Sascha Zertani, and Frederik Tilmann designed the project. Sascha Zertani, Timm John and Loic Labrousse collected the samples. Hem B. Motra measured P and S wave velocities in the laboratory (Kiel) with help and instructions from Sascha Zertani and Sascha Zertani interpreted the resulting data. Sascha Zertani performed the thermodynamic calculations on the basis of XRF whole rock data that were measured at the GFZ Potsdam by Andrea Gottsche. Neutron diffraction measurements were performed at the Joint Institute of Nuclear Research (JINR) in Dubna (Russia) by beamline scientist Robert Kurzawski and Sascha Zertani. Ruth Keppler refined the results and Sascha Zertani interpreted the data. Frederik Tilmann calculated the reflection response and receiver function response of the shear zones on the basis of the data provided by Sascha Zertani. Sascha Zertani combined all results, interpreted the data, and wrote the manuscript. All coauthors commented on various versions of the manuscript and participated in discussions that lead to the final conclusions.

Chapter 4 (in preparation to be submitted to *Geochemistry, Geophysics, Geosystems*)

This chapter aims to bridge the scale gap that exists between field observations and those from large-scale geophysical methods. In this regard, realistic structures and geometries that are thought to be representative of the structures that stem from partial eclogitization are utilized to calculate effective P wave velocities on the scales intermediary between those used in the field and laboratory and those utilized by geophysical methods. This is done using the finite element method.

Timm John, Sascha Zertani, and Frederik Tilmann designed the project. Sascha Zertani and Johannes C. Vrijmoed wrote the MATLAB code with significant input from Frederik Tilmann. Sascha Zertani interpreted the results and wrote the manuscript. All authors commented on various versions of the manuscript and participated in discussions.

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Chapter 2

The interplay of eclogitization and deformation during deep burial of the lower continental crust – A case study from the Bergen Arcs (Western Norway)

Key Points

- The fluid-induced eclogitization on Holsnøy is controlled both dynamically by shear zone development and static equilibration
- Eclogite-facies shear zone geometry on Holsnøy is scale-independent from centimeter to kilometer scale

Published as:

Zertani, S., Labrousse, L., John, T., Andersen, T.B., & Tilmann, F. (2019). The Interplay of eclogitization and deformation during deep burial of the lower continental crust – A case study from the Bergen Arcs (Western Norway). Tectonics, 38, 898-915. https://doi.org/10.1029/2018TC005297

Chapter 3

Modification of the seismic properties of subducting continental crust by eclogitization and deformation processes

Key Points

- *Eclogitization of continental crust increases seismic velocities (isotropic averages up to 8.21 km/s) and decreases V_P/V_S ratios by ~0.04.*
- *Eclogitization coeval with deformation causes a high P wave anisotropy of up to 9%.*
- *Shear zone formation coeval with eclogitization causes changes of the seismic response of the structure.*

Published as:

Zertani, S., John, T., Tilmann, F., Motra, H.B., Keppler, R., Andersen, T.B., & Labrousse, L. (2019). Modification of the seismic properties of subducting continental crust by eclogitization and deformation processes. Journal of Geophysical Research: Solid Earth. 124, 9731-9754. https://doi.org/10.1029/2019JB017741

Chapter 4

P wave anisotropy caused by partial eclogitization of subducting crust demonstrated by modelling effective petrophysical properties

Key Points

- *Eclogitization of crustal rocks causes significant anisotropy on a crustal scale*
- *Geometric arrangement has no significant influence on effective seismic properties*
- *Backazimuthal bias in receiver function studies can be caused by eclogitization*

Submitted to *Geochemistry, Geophysics, Geosystems*:

Zertani, S., Vrijmoed, J.C., Tilmann, F., John, T., Andersen, T.B., & Labrousse, L. (in preparation). P wave anisotropy caused by partial eclogitization of subducting crust demonstrated by modelling effective petrophysical properties.

Preprint DOI: https://doi.org/10.31223/osf.io/phybg

Chapter 5

Conclusions and Outlook

5.1 Conclusions

Processes active at depth in subduction and collision zones are not directly observable. Traditionally, the structures and geometries in active settings are studied by geophysical imaging techniques, and the ongoing processes are inferred from the retrieved seismic signal. Contrarily, fossil subduction and collision zones are utilized to study the resulting structural associations and petrology directly. It is, however, unclear if these exposures are representative of the structures at depth. This thesis aims at bridging the gap between seismological and field-based studies, specifically, in the regarding subducting and collision zones.

Mapping of the partially eclogitized lower crust exposed on Holsnøy shows that fluid-induced eclogitization proceeds via the interplay of two main mechanisms. Either, eclogitization is coeval with ductile deformation forming eclogite shear zones that widen progressively with time. These are surrounded by an alteration halo, which has the form of an eclogite breccia when the shear zones are evolved and large. Secondly, eclogitization proceeds statically, that is, without associated ductile deformation. In this case, patches of static eclogitization originate from the fracture that initially introduced the fluids into the rock. Static eclogitization patches are irregular, however, they often consume the preexisting granulite parallel to its foliation. Our new geological map of Holsnøy shows that the static form of eclogitization is significantly more extensive than previously thought. Large areas of this crustal section are transformed without associated deformation forming low-strain domains between the main shear zones during ongoing regional deformation.

Additionally, our results suggest that the structures that are established during partial eclogitization are scale-independent, at least in a qualitative sense. Shear zones, independent of their length and thickness are surrounded by an alteration halo. For shear zones that are only a few centimeters thick, the surrounding zone provides a smooth transition from an eclogite-facies assemblage to the original granulite-facies assemblage. The shear zone networks are characterized by a surrounding zone with less and smaller shear zones, thus also constituting a gradual transition into the unaltered granulite, and the main shear zones are surrounded by the eclogite breccia, which also provides a transition from eclogite to granulite. Further, from the meter scale to the map scale the shear zones surround the aforementioned low-strain domains. This scale-independence combined with the notion that large parts of the rock volume were eclogitized statically suggests that even on larger scales, within active subduction and collisions zones the general structural framework will be characterized by similar geometries.

P and S wave velocity measurements have shown that eclogitization of the lower crust is coeval with an increase of the seismic velocities of ~0.8 km s^{-1} for P waves and 0.6 km s^{-1} for S waves. Additionally, when associated with ductile deformation the seismic anisotropy increases from the protolith to the eclogite. The maximum P wave anisotropy obtained in this study is 9%, which is significantly higher than anisotropies typically reported for eclogites. Furthermore, the granulite-to-eclogite transition leads to a decrease of the V_P/V_S ratio of 0.04 (from ~1.80 to ~1.76).

Our results therefore show that eclogitization of crustal rocks is coeval with a significant change of the seismic properties. These distinct differences between the lithologies can be indicative of ongoing eclogitization in seismological studies of active subduction and collision zones. The variation in seismic velocities in combination with the changing V_P/V_S ratios should be sufficient to produce boundaries with a detectable impedance contrast. Additionally, the increased P wave anisotropy will lead to a backazimuthal dependence of the retrieved signal in, for example, receiver function studies.

The structures exposed on Holsnøy, however, are too small to be resolved by geophysical methods at depth. While simplified shear zone models and the calculated synthetic reflection and receiver function response suggest that these structures indeed produce distinctly different responses, the frequencies used are not feasible for large-scale seismological studies. On the one hand, the apparent scale-independence of the structures suggests that similar structures at a larger scale could be present in active subduction and collision zones. However, it is vital for our interpretation of the structures at depth to understand how structures on scales below those that are resolvable by geophysical imaging, shape the seismic properties of an effective medium with geometries realistic for natural processes.

To calculate the properties of effective medium numerical calculations using the finite element method were conducted on a suite of different geometries with varying initial petrophysical properties. The calculations reveal that the geometry itself only has a minor influence on the properties of the effective medium. P wave velocities of the effective medium are entirely dependent on the P wave velocities of the constituting lithologies. P wave anisotropy, however, is mostly controlled by the anisotropy of the constituting lithologies and on their internal geometry, i.e., the orientation of the fast and slow axis of the different lithologies to one another.

Nevertheless, our effective medium calculations reveal that the P wave anisotropy of an effective medium produced during eclogite-facies metamorphism and coeval ductile deformation in a subduction or collision zone can be significant. Modelling of the central part of the partially eclogitized area of Holsnøy reveals that the entire shear zone system would have a P wave anisotropy of ~5%. This is directly transferable to, for example, the Himalaya-Tibet collision system and suggests that the backazimuthal dependence on the retrieved receiver function signal that is observed in the Indian lower crust can be interpreted as a shear zone system along which the crust is actively eclogitizing at present. The results of this thesis thus provide direct observations that can be combined with teleseismic studies focusing on subduction and collision zones using observations from structural geology, petrology, petrophysics and seismology to form a coherent picture of eclogitization at depth.

5.2 Outlook

The results presented in this thesis have significant implications for seismic imaging of subduction and collision zones. However, there is still work needed to fully understand the processes going on at depth. From our results it is clear that geophysical imaging studies need to put a clear focus on the anisotropy of seismic waves. It has been shown that a backazimuthal dependence of the retrieved signal reveals structures at depth in collision zones that would be invisible otherwise. In the future this approach needs to be used systematically also in (oceanic) subduction zones. This way it might be possible in the future to detect eclogites at depth and thus significantly extend the range in which subduction can be imaged. Additionally, better imaging of the structures at depth will enhance our knowledge of how crustal recycling proceeds. Further, a better understanding of the geometries at depth will also help to unravel processes such as fluid flow in high pressure regimes, the exhumation of high pressure units and whether the lithologies and structures that have been exhumed to the surface are actually representative of the structures at depth.

Furthermore, our results show how P wave anisotropy varies for different lithologies. These models need to be extended to also include S waves. Here, a 3D finite element approach seems most promising. That way we can gather 3D information on the variation of P and S wave velocities for both cylindrical and non-cylindrical structures below active orogens.

Appendix A

Related publications

This section contains all publications related to this dissertation. This includes the publications that form chapters 2 and 3, as well as co-authored publications and conference contributions.

A.1 Peer-reviewed publications

Zertani, S., John, T., Tilmann, F., Motra, H. B., Keppler, R., Andersen, T. B., & Labrousse, L. (2019). Modification of the seismic properties of subducting continental crust by eclogitization and deformation processes. Journal of Geophysical Research: Solid Earth. 124, 9731-9754. https://doi.org/10.1029/2019jb017741

Zertani, S., Labrousse, L., John, T., Andersen, T. B., & Tilmann, F. (2019). The interplay of eclogitization and deformation during deep burial of the lower continental crust–A case study from the Bergen Arcs (western Norway). Tectonics. 38, 898-915. https://doi.org/10.1029/2018tc005297

Motra, H. B., & **Zertani, S.** (2018). Influence of loading and heating processes on elastic and geomechanical properties of eclogites and granulites. Journal of Rock Mechanics and Geotechnical Engineering. 10, 127-137. https://doi.org/10.1016/j.jrmge.2017.11.001

A.2 Conference contributions

Zertani, S., John, T., Vrijmoed, J. C., Tilmann, F., Labrousse, L., & Andersen, T. B. (2019). The variation of petrophysical properties during eclogitization of lower continental crust and their influence on geophysical imaging. EGU General Assembly 2019, 15813, Vienna, Austria, Oral presentation.

Kaatz, L., **Zertani, S.**, Moulas, E., John, T., Labrousse, L., Schmalholz, S., & Andersen, T. B. (2018). Evolution of hydrous shear zones during incipient eclogitization of metastable dry and rigid lower crust (Holsnøy, Western Norway). EGU General Assembly 2018, 8002, Vienna, Austria, Poster Presentation.

Zertani, S., John, T., Tilmann, F., Labrousse, L., & Andersen, T. B. (2018). The effect of eclogitization and associated deformation on the petrophysical properties of lower continental crust. EGU General Assembly 2018, 8893, Vienna, Austria, Oral Presentation.

Zertani, S., John, T., Tilmann, F., Labrousse, L., Motra, H. B., & Andersen, T. B. (2017). The influence of eclogitization of lower crustal rocks on receiver functions. GeoBremen, Annual Meeting of DGGV & DMG. A-502, Bremen, Germany, Oral Presentation.

Zertani, S., John, T., Tilmann, F., Motra, H. B., Labrousse, L., & Andersen, T. (2017). Petrophysical properties of eclogite facies shear zones and their relationship to receiver function signals. EGU General Assembly 2017, 18686, Vienna, Austria. Poster Presentation.

Zertani, S., John, T., Tilmann, F., Motra, H. B., Labrousse, L., & Andersen, T. B. (2017). Seismic properties of eclogite facies shear zones in subducted lower crust. Subduction Interface Processes International Conference, SIP34, Castelldefells, Spain. Oral Presentation.

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Appendix B

Supporting information of "The interplay of eclogitization and deformation during deep burial of the lower continental crust–A case study from the Bergen Arcs (western Norway)" – Chapter 2

The supporting information of this article is not available in the online version due to copyright restrictions and be accessed via https://doi.org/10.1029/2018TC005297.

Appendix C

Supporting information of "Modification of the seismic properties of subducting continental crust by eclogitization and deformation processes" – Chapter 3

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Appendix D

Supporting information of "P wave anisotropy caused by partial eclogitization of subducting crust demonstrated by modelling effective petrophysical properties" – Chapter 4

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Curriculum Vitae

The curriculum vitae is not available in the online version due to personal data protection.

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