Abschlussbericht DFG Projekt COSTMAR

COstraining the SeismoTectonics, crustal, and uppermost mantle structure beneath an actively propagating segment of the northen Mid-Atlantic Ridge at 21.5N

Geophysikalische Untersuchungen zur Seismotektonik, Krusten- und Mantelstruktur im Bereich eines propagierenden Rückensegments am Mittelatlantischen Rücken bei 21.5°N

DFG Grants Mo 961/5-1 (Jason Phipps Morgan, FrederikTilmann, Cesar Ranero),
Ra 925/5-1 (Cesar Ranero, Ingo Grevemeyer),
Gr 1964/8-2 + 8-3 (Ingo Grevemeyer)

IFM-GEOMAR
Leibniz-Institut für Meereswissenschaften
an der Universität Kiel

1. GENERAL INFORMATION / ALLGEMEINE ANGABEN

Final Report of grants Mo 961/5-1 (Phipps Morgan, Tilmann, Ranero),
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1.2 TITLE / THEMA

COSTMAR – Constraining the seismotectonics, crustal and uppermost mantle structure beneath an actively propagating segment of the northern Mid-Atlantic Ridge

1.3 FUNDING PERIOD / FÖRDERUNGSZEITRAUM

R/V *Meteor* Expedition M60/2 Mo 961/5-1: December 8, 2003 to January 12, 2004
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1.4 LIST OF PUBLICATIONS / LISTE DER PUBLIKATIONEN

Dannowski, A, I. Grevemeyer, C.R. Ranero, G. Ceuleneer, M. Maia, J. Phipps Morgan, P. Gente, Seismic structure of an oceanic core complex at the Mid-Atlantic Ridge, 22°19'N, J. Geophys. Res., in press, 2009a

Dannowski, A., Processes of magmatic and tectonic accretion of oceanic lithosphere at mid-ocean ridges: constraints from a seismic refraction study at the Mid-Atlantic Ridge near 21.5° N, Dissertation, Christian-Albrechts Universität zu Kiel, pp. 165, 2009

Kahle, R.L., A seismic investigation of the 21.5° propagating segment on the Mid-Atlantic Ridge, Dissertation, St. John's College, University of Cambridge, pp. 176, 2007

2. REPORT / ARBEITS- UND ERGEBNISBERICHT

2.1 AIMS AND GOALS / AUSGANGSFRAGEN UND ZIELSETZUNG DES PROJEKTS

Ridge propagation is one of the best known but least understood aspects of plate tectonics. Thus, while transform faults, spreading centres, and convergent trenches are all "required" elements of seafloor spreading on a constant-volume sphere, propagating ridges (PRs), where one spreading segment grows at the expense of its neighbour, were unexpected that their discovery took 20 year after they were first mapped magnetically at the Juan de Fuca spreading axis (in Raff and Mason's famous map of magnetic "stripes"). More importantly, ridge propagation provides an important natural laboratory with which scientist can explore the processes governing ridge crest segmentation.

Transform fault boundaries are so called first order segment boundaries of spreading ridges and are generally extraordinary stable – many of the initial offsets of Atlantic rifting have remained continuous transform offsets during the subsequent 100+ Mio. years spreading history of the Atlantic ocean. However, in some rare cases transform faults are not stable and a propagating ridge segment develops. Therefore, the existence of a propagating ridge suggests a segmentation pattern that is particularly unfavourable, promoting rifting and extension of relatively thick abutting lithosphere. Thus, ridge propagation differs from a migrating second- or third-order non-transform offset (like overlapping spreading centres along the East Pacific Rise), where migration is possible without the need for the extending segment to break into older lithosphere. However, a satisfactory geodynamical model for ridge propagation has yet to be proposed. Indeed, the nature of ridge segmentation in general has yet to be fully understood. Attempts to describe propagation using fracture mechanics and stress field modeling (Morgan and Parmentier, 1985) have yielded some insight, though no consensus or consistent model exists. Morgan and Sandwell (1994) point out that most of the known propagating ridges extend away from bathymetric highs and suggest a model of fracture extending down a gravitational gradient. Equally plausible, however, is that increased melt at the propagating ridge results in a weaker axial centre, thus promoting rifting at the propagating segment (West et al., 1999). Because of the difficulties of addressing the problem of propagating ridges, there has been little advance in our understanding of them since the early 1990s.

Ridge propagation has been studied at fast- and intermediate spreading ridges since the early 1980s, with work concentrating on the 95°30'W PR of the Cocos-Nazca spreading centre. Geophysical work focused on multibeam bathymetric mapping, magnetic, and gravity studies. The sheared zone connecting the propagating and dying ridges (called the doomed ridge, see Figure 1) was found, at intermediate- and fast-spreading rates, to be a zone of distributed deformation, although debate remains to the extent which deformation occurs on transform-parallel strike slip faults versus bookshelf faulting on reactivated ridge normal faults (Phipps Morgan and Kleinrock, 1991).

The 95°30'W propagating ridge in the equatorial Pacific has been the only PR that has been investigated using seismic methods in addition to satellite altimetry and ship-borne bathymetric and potential field mapping efforts: thus, there has never been a detailed geophysical study of ridge propagation in a median valley slow-spreading environment. Therefore, the COSTMAR cruise was conducted aboard R/V *Meteor* in December 2003 and January 2004, exploring ridge propagation at the Mid-Atlantic Ridge (MAR) near 21°30'N (Figure 2), where a PR developed roughly 5 Mio. years ago, forming a V-shaped trace on the seafloor. Bathymetric features associated with ridge propagation can best be explained describing ridge propagation tectonics geometrically. A simple mathematical model proposed by McKenzie (1986) is known as broad transform zone propagation. This model assumes that the propagating ridge extends at a constant rate as it takes over the spreading role from its neighbour, known as the doomed ridge (DR). As it does so, it leaves behind a characteristic footprint of two pseudofaults (PF) in the shape of a V. These pseudofaults demarcate the boundary between crust which has been created by each respective ridge segment. Spreading responsibilities are transferred from one ridge segment to the other over a finite distance. This creates a transform zone (TZ) between the propagating ridge and the doomed ridge, now called the failing ridge. Once it has completely ceased to be active, the failing ridge is known as the failed ridge (fR). Within the transform zone, active deformation takes place as material shears in the process of being transferred from one plate to the other. This results in a sheared zone (SZ) between the failed ridge and its inner pseudofault (Figure 1).

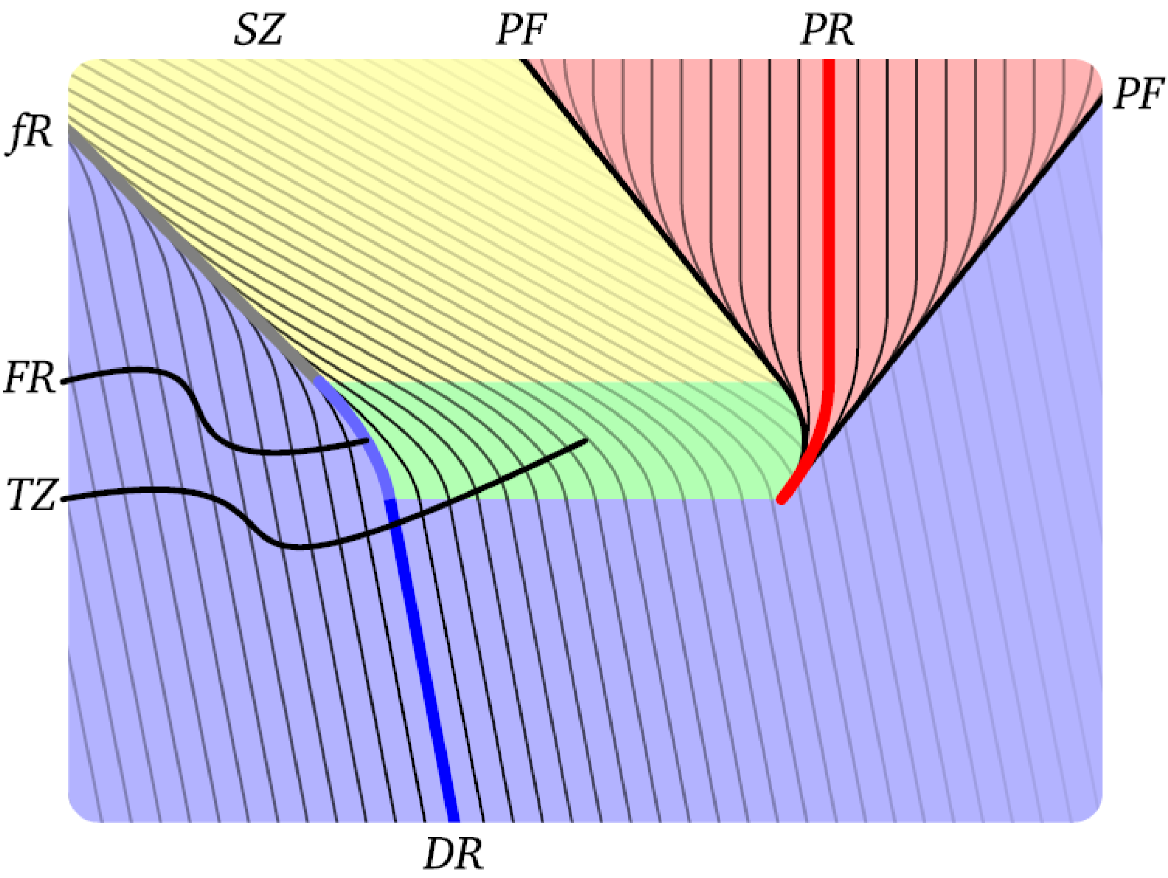

Figure 1. Schematic diagram of propagating ridge tectonics according to the broad transform zone kinematic model. Tectonic elements shown are the propagating ridge (PR), doomed ridge (DR), failing ridge (FR), failed ridge (fR), transform zone (TZ), sheared zone (SZ) and the inner and outer pseudofaults (PF). The parallel lines indicate isochrons and fade with age. The doomed ridge is depicted at a marginally oblique angle for generality and to match, roughly, the bathymetric features of this study. The propagation direction is down the page.

During the COSTMAR cruise, four seismic profiles have been placed to study ridge propagation (Figure 2). P02 runs along the ridge crest studying crustal structure of the PR and its termination, yielding insights into the along axis crustal structure and magma distribution caused by ridge propagation (remark: Some stations failed along P02. Therefore, parts of P02 have been surveyed again along P06, that has been integrated in P02). P04 and P5 run obliquely to the ridge crest, surveying the crustal variability at the magmatically most active segment centre as a function of time. P03 crossed the ridge crest and sampled seismically the structure of the so called shear zone. While magmatic activity is expected dominating lithospheric construction during ridge propagation, architecture of lithosphere at slow spreading ridges occurs often asymmetrically and causes amagmatic extension and hence core complex formation. This contrasting mode of accretion is studied along P08 to the north of the propagation segment. Figure 2 provides an overview of all seismic lines. In addition, a micro-earthquake study has been conducted surveying earthquake activity at the tip of the PR and in the transform zone, connecting the PR and the doomed ridge.

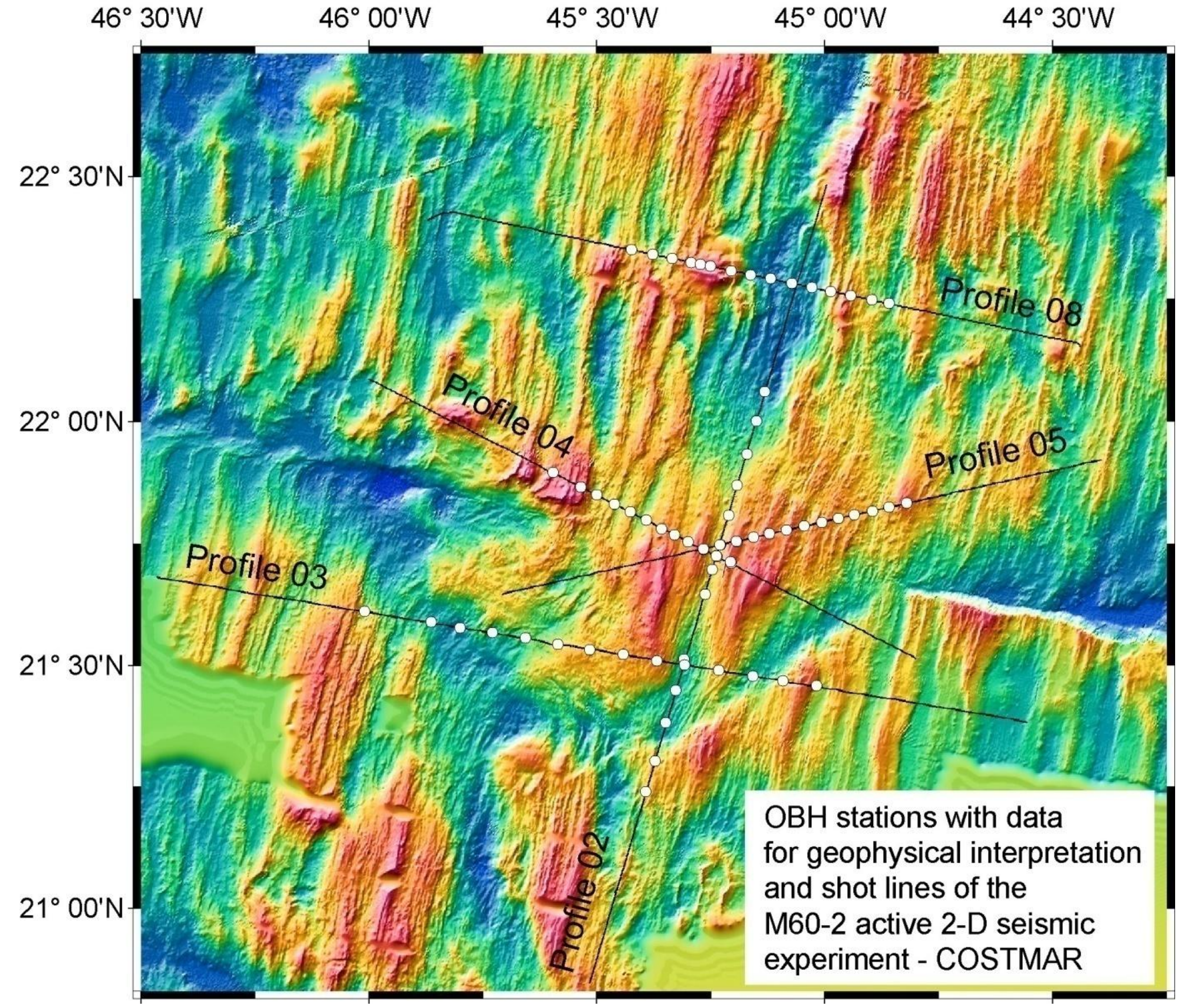

Figure 2. Seismic refraction lines obtained within the project COSTMAR (R/V *Meteor* cruise M60/2) along the Mid-Atlantic Ridge between 21°N and 22°30'N. Note the transform fault near 22°N that failed and V-shaped wake of ridge propagation.

2.2 Results and Discussion / Darstellung der erreichten Ergebnisse und Diskussion im Hinblick auf den relevanten Forschungsstand

The data obtained during the R/V *Meteor* cruise M60/2 in 2003/2004 provided for the first time detailed information on the crustal structure caused by ridge propagation, both at the ridge axis and in the broad transform and shear zone replacing an old well located transform fault. Data allowed us to study the along axis variability of crust, the structure of the segment centre as a function of time (~4 Mio. years) and the structure of the sheared zone connecting the propagating ridge tip with the adjacent doomed ridge segment, an area of active deformation. In addition, micro-earthquakes from the transform zone have been recorded, providing the first micro-earthquake study of tectonic processes facilitating stresses between the propagating ridge and the doomed ridge segment.

Furthermore, we reported for the first time results of a seismic refraction and wide-angle reflection profile crossing an oceanic core complex and its genetically associated conjugated ridge flank, providing data from a hanging wall and footwall of a detachment fault system.

Travel time data obtained along the ridge crest of the propagating segment (i.e., profiles p02 and p06) have been inverted using seismic tomography yielding seismic velocities and indicates that crust is with 8 km thickest in the segment centre and thins towards segment ends (Dannowski, 2009; Dannowski et al., 2009b). At the northern segment end crust thins to 4 km, while at the southern end crust is ~6 km. The seismic velocity structure is typical of oceanic crust formed at magmatic spreading centres. However, it is interesting to note that the thickness of seismic layer 2 is almost constant along the profile while differences in total crustal thickness occur in layer 3, with a thicker layer 3 in the segment centre, thinning approaching segment boundaries (Figure 3). These features suggest focused melt supply at the segment centre and lateral redistribution of melt. Thus, low viscosity basalts are easily distributed along axis, while lower viscosity gabbros tend to stay where magma upwelling occurs. Further, thicker crust in the direction of ridge propagation may suggest that magma transport (or dyking) away from a centre of mantle upwelling is driving ridge propagation.

Seismic lines P04 and P05 sampled the crustal structure of the segment centre as a function of age on the American and African plate, respectively. Crustal thickness remains with 8 km +/- 0.5 km reasonable constant (Figure 3), suggesting that melt supply was constant during the time of ridge propagation, too (Dannowski, 2009; Dannowski et al., 2009). Further details on the crustal structure of the propagating ridge are discussed in the dissertation of Dannowski (2009) and in the manuscript of Dannowski et al. (2009b).

Seismic line P03 surveyed the crustal structure across the propagating ridge-tip and in the sheared zone that accommodated the strike-slip motion during ridge propagation (see chapter 2 of Kahrle, 2007). Seismic tomographic inversion indicates that crust formed at the propagating ridge is thicker than in the adjacent shear zone, where crust is extraordinarily thin, with the Moho lying only 4 km below the seafloor (Figure 4). A steep velocity gradient runs through the entire depth of the crust. A clear age dependence in the uppermost velocities to the west of the failed ridge, between the two pseudofaults, and to the east of the outer pseudofault is evident. This is in accordance with observations made by Grevemeyer and Weigel (1996) and is related to hydrothermal precipitation of minerals in open void spaces. Uppermost velocities in the sheared zone are very low, however, and do not display this age dependence. A very steep velocity gradient is evident in the shallow crust of the sheared zone. This would be consistent with peridotite denudation and subsequent serpentinisation.

The seismic monitoring network has been operated for roughly 6 month in 2004 (see chapter 3 of Kahrle, 2007). In total 4674 micro-earthquakes were detected (Figure 5). However, 548 could be classified as well located. Event distribution suggests that the propagating ridge is seen to be virtually aseismic, indicating a thin lithosphere and hence supporting a magmatically active setting. One significant cluster of events is observed, though, and might be of magmatic origin. The doomed ridge exhibits strong seismicity. It is concentrated on its eastern flank at a so-called inside corner setting, often found to be dominated by amagmatic extension, causing core complex formation (see discussion of P08). Events tend to occur in swarms, with one particularly large swarm making up approximately half of the doomed ridge events during the recording period. The b-value of events during the swarm period is very low (0.77), while that for all other doomed ridge events is particularly high (1.4). This suggests a low background seismicity of small events punctuated by swarms of much larger magnitude earthquakes. Such high magnitude swarming is characteristic of mechanical rifting on the MAR (Bergman and Solomon, 1990) and implies a strong seismogenic layer

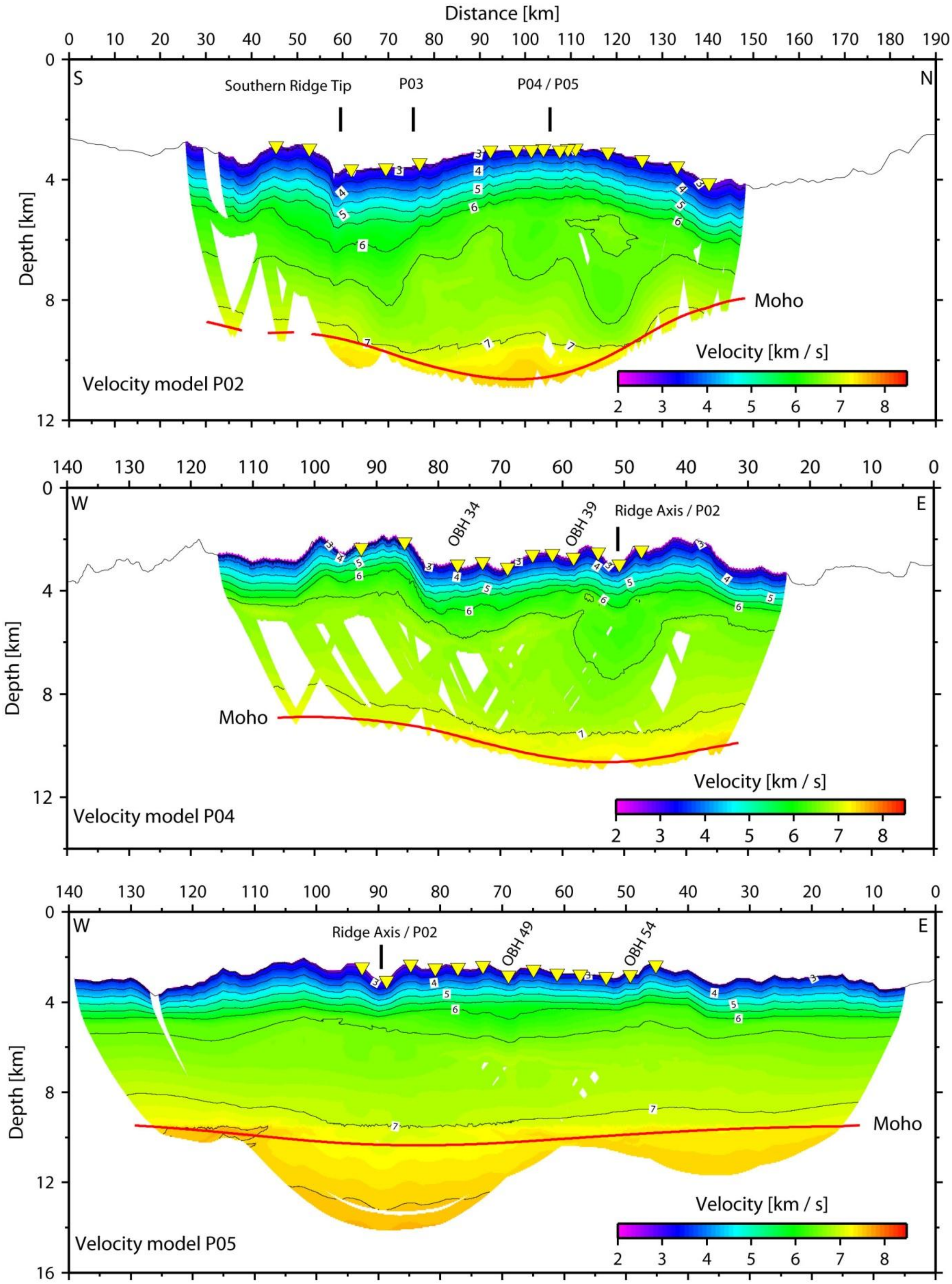

Figure 3. Seismic velocity models obtained from tomographic travel time inversion of seismic refraction and wide-angle reflection data along the propagating ridge segment (P02) and along the mid-segment centre as a function of age on the American plate (P04) and on the African plate (P05). See Dannowski (2009) for details on modeling and further discussion of results.

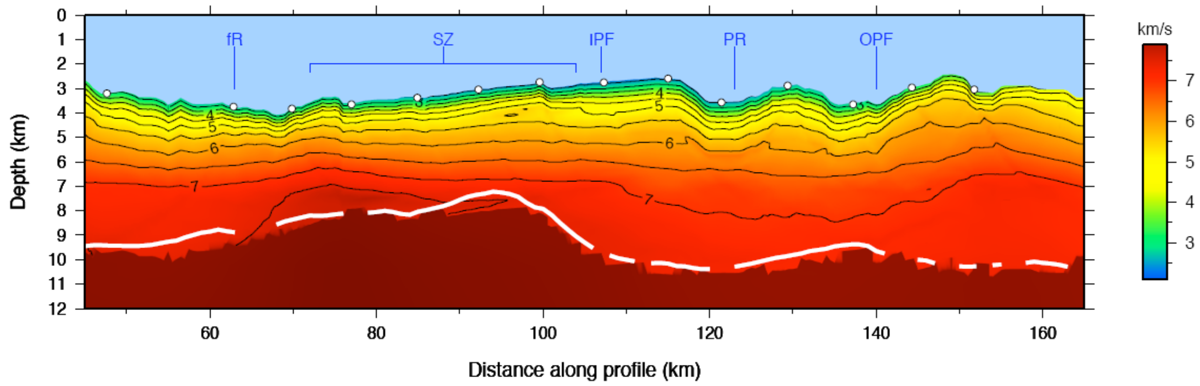

Figure 4. Seismic velocity model from P03 crossing the outer-pseaudofault (OPF), the propagating ridge (PR), the inner-pseudofault (IPF), the shear zone (SZ) indicating bookshelf faulting and hence thinning, and the failed ridge (fR). Details are given by Kahle (2007).

with a high yield strength. Strong seismicity was also observed in the transform zone, although this was not spatially uniform, with the majority of events concentrated in the eastern half. Small-scale structure is apparent in the seismicity, with many events aligning themselves on features perpendicular to the direction of spreading. This structure suggests that old normal faults generated during rifting are reactivated to accommodate deformation within the transform zone. The event set is characterized by a relatively high b-value (1.24) implying a low yield strength and a preponderance of small events. No swarming is evident. The possibility exists that swarms do occur but one simply was not recorded. A small scale systematic pattern of events aligning on planes is evident in the transform zone. These planes strike perpendicular to the spreading direction and dip towards the east, suggesting that normal faults generated during spreading are being reactivated to accommodate deformation in the transform zone. This is in agreement with the bookshelf faulting model for transform zone migration of Phipps Morgan and Kleinrock (1991). Figure 5 shows a summary map of the event distribution.

Profile P08 provides seismic refraction and wide-angle data surveying an oceanic core complex on the Mid-Atlantic Ridge at 22°19'N. Oceanic core complexes are settings where petrological sampling found exposed lower crustal and upper mantle rocks, probably exhumed by asymmetric crustal accretion involving detachment faulting at magmatically starved ridge sections. Tomographic inversion of the seismic data yielded lateral variations of P-wave velocity within the upper 3 to 4 km of the lithosphere across the median valley (Figure 5). A joint modelling procedure of seismic P-wave travel times and gravity data was used to constrain crustal thickness variations and the structure of the uppermost mantle. A gradual increase of seismic velocities from the median valley to the east is connected to ageing of the oceanic crust (e.g., Grevemeyer and Weigel, 1996), while a rapid change of seismic velocities at the western ridge flank indicates profound differences in lithology occurring under conjugated ridge flanks, caused by un-roofing lower crust rocks at the core complex. Under the core complex crust is approximately 40% thinner than in the median valley and under the conjugated eastern flank. Clear PmP reflections turning under the core complex suggest the creation of a Moho boundary and hence continuous magmatic accretion during core complex formation. This is the first time that seismic data provided clear evidence for asymmetric magmatic accretion, using data coverage of both ridge flanks and hence surveying the footwall or core complex and the hanging wall crust in the median valley and under the conjugated ridge flank. Results are presented in the thesis of Dannowski (2009) and in a paper (Dannowski et al., 2009a).

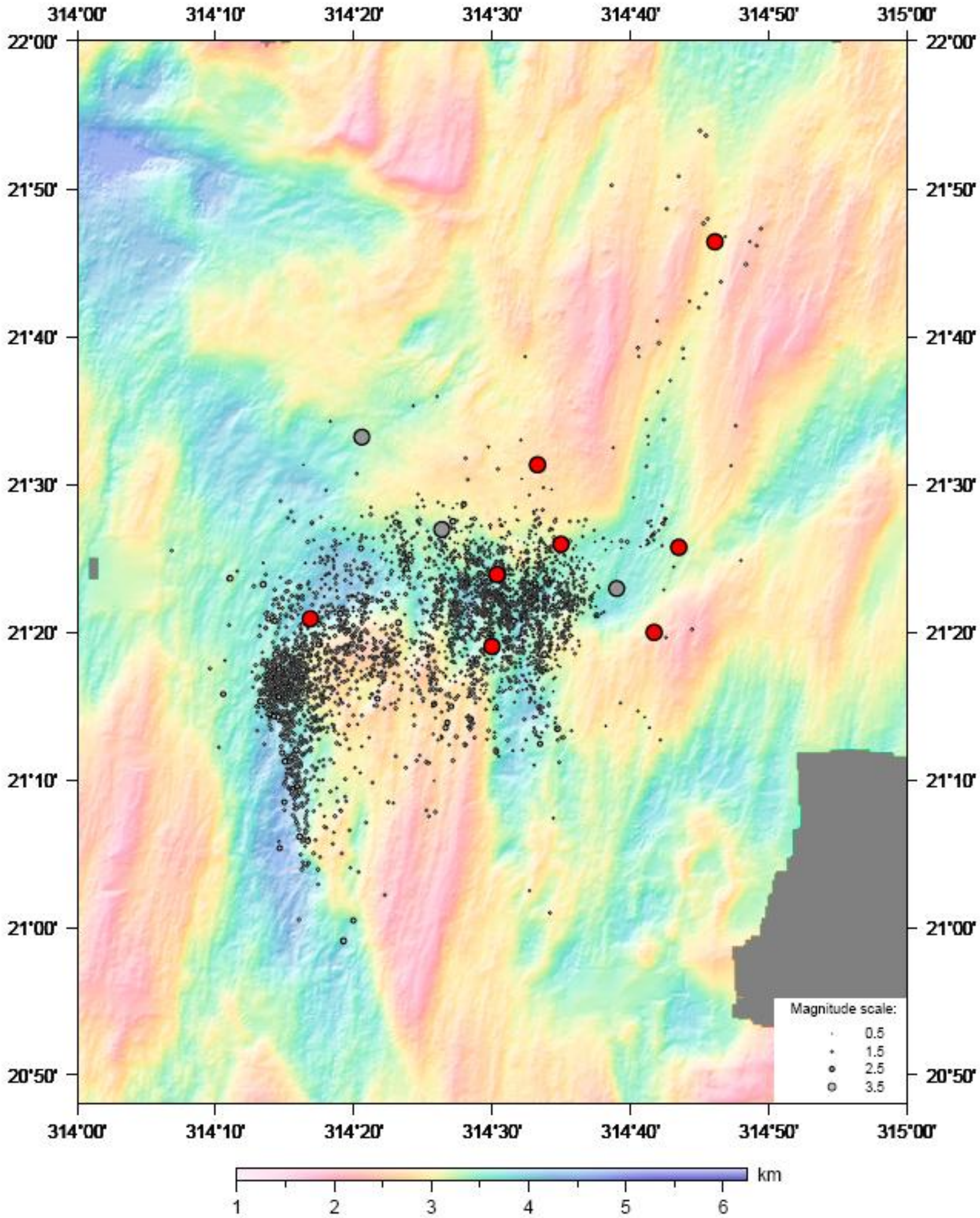

Figure 4. Map showing the micro-earthquake activity recorded during a 6 month deployment of ocean bottom seismic stations (red and grey circles – grey circles mark stations that failed to record for the entire deployment time). In total 4674 events have been recorded and located (see for details Kahle, 2007).

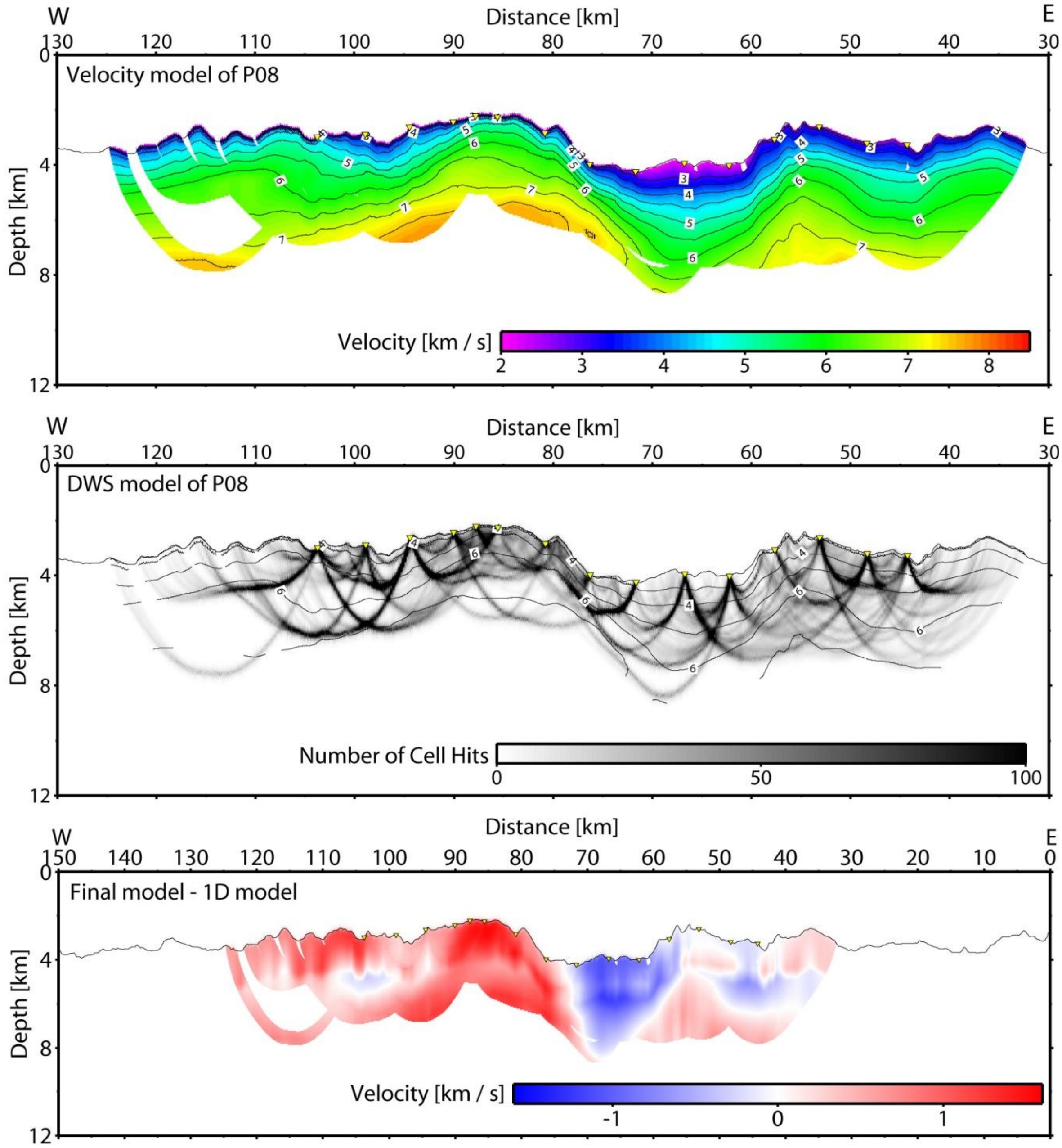

Figure 5. Seismic velocity model of crustal arrival tomography supporting different lithology forming conjugated the ridge flanks. This feature is best seen in the lower panel, where a 1-D reference model has been subtracted. Note: fast velocities dominate at the western flank, while lower than average velocities occur in the median valley. The structure of the eastern flank closely resembles the reference model.

2.3 Qualification of Students and Young Scientists / Qualifikation des wissenschaftlichen Nachwuchses im Zusammenhang mit dem Projekt

Dissertationen

Dannowski, A., Processes of magmatic and tectonic accretion of oceanic lithosphere at mid-ocean ridges: constraints from a seismic refraction study at the Mid-Atlantic Ridge near 21.5° N, Dissertation, Christian-Albrechts Universität zu Kiel, pp. 165, 2009

Kahle, R.L., A seismic investigation of the 21.5° propagating segment on the Mid-Atlantic Ridge, Dissertation, St. John's College, University of Cambridge, pp. 176, 2007

Tagungsbeiträge der Doktoranden im Rahmen ihrer Ausbildung

Dannowski, A., I. Grevemeyer, J. Phipps Morgan, C.R. Ranero, Crustal structure of a propagating ridge segment from seismic refraction and wide-angle data (Poster), American Geophysical Union, Fall Meeting San Francisco, 2007.

Dannowski, A., I. Grevemeyer, J. Phipps Morgan, C.R. Ranero, Crustal structure of a propagating ridge segment from seismic refraction and wide-angle data (Poster), Annual Meeting of the European Geophysical Union, Vienna, 2008.

Dannowski, A., I. Grevemeyer, Ingo, C.R. Ranero, M. Maia, J. Phipps Morgan, Oceanic core complex structure derived from seismic refraction and wide-angle reflection data (Poster), American Geophysical Union, Fall Meeting San Francisco, 2008.

Kahle, R.L., A. Dannowski, F. Tilmann, I. Grevemeyer, Seismic constraints on a propagating ridge system (Poster), American Geophysical Union, Fall Meeting San Francisco, 2006.

3. ZUSAMMENFASSUNG

Im Rahmen des seegeophysikalischen Projekts COSTMAR wurde erstmalig die Krustenstruktur eines propagierenden Rückensegments am Mittelatlantischen Rückens bei 21°30'N während der Reise M60/2 des FS *Meteor* mittels tiefenseismischer Messungen untersucht. Ein propagierendes Rückensegment bildet sich, wenn z.B. durch Änderungen in der Bewegungsrichtung der tektonischen Platten eine Transformverwerfung instabil wird und die Spreizungsachse sich lateral ausbreitet und alte ozeanische Lithosphäre aufbricht. Insgesamt wurden vier refraktions- und weitwinkelseismische Profile abgeschossen, um die Krustenstruktur, den Schmelztransfer und tektonische Prozesse in der sich neubildenden und das Segment (südlich) begrenzenden Transformzone abzubilden. Darüber hinaus sollten zeitliche Aktivitätsschwankungen in der Schmelzproduktion untersucht werden. Hierzu wurden zwei V-förmig verlaufende Profile auf der Amerikanischen und Afrikanischen Platte platziert, um durch Schwankungen in der Mächtigkeit der Kruste in der Paläo-Segmentmitte einen Indikator für Änderungen in der Schmelzproduktionsrate zu bekommen. Das vierte Profil kreuzte die Rückenachse und die Scherzone, um die Krustenstruktur in der Paläo-Transformzone abzubilden. Darüber hinaus registrierte ein Netzwerk aus Ozeanbodenseismometern die lokale Erdbebenaktivität im Bereich des propagierenden Rückensegments sowie in der Scherzone am Segmentende.

Entlang der Rückenachse wurde die größte Krustenmächtigkeit in der Segmentmitte beobachtet. Diese nimmt von der Segmentmitte mit ca. 8 km Mächtigkeit zu den Segmentgrenzen hin ab. Am nördlichen Ende des Segments war die Kruste mit 4 km am dünnsten. Am südlichen Ende, in Propagationsrichtung, war die Kruste mit ca. 6 km deutlich mächtiger. Diese Beobachtung deutet darauf hin, dass Schmelzen in der Segmentmitte aufsteigen und zu den Segmentenden hin transportiert werden. Die größere Mächtigkeit in Propagationsrichtung kann dadurch erklärt werden, dass die Propagation durch lateralen Schmelztransfer getrieben wird. Über die letzten 5 Mio. Jahre, d.h., seit Beginn der Propagation, wurde in der Segmentmitte eine Kruste mit nahezu konstanter Mächtigkeit von ca. 8 km gebildet. D.h., die Schmelzproduktionsrate scheint über die Zeit nahezu konstant geblieben zu sein. Die Scherzone hat mit nur 4-5 km die geringste Krustenmächtigkeit. Die Registrierung und Tiefenverteilung von über 4000 lokalen Erdbeben mit Magnituden von M_L=0.5 bis 3.5 deutet darauf hin, dass die Kruste durch sog. „Bookshelf faulting" ausgedünnt worden ist. Somit ist es erstmalig gelungen den Spannungstransfer zwischen einem sich ausbreitenden Spreizungssegments und des benachbarten Segments abzubilden. Hier standen sich bislang zwei konkurrierende Vorstellungen geben über: „Bookshelf faulting" und somit Reaktivierung von an der Spreizungsachse gebildeter Störungen bzw. ‚reine' Blattverschiebung.

Darüber hinaus wurde ein fünftes tiefenseismisches Profil nördlich des propagierenden Segments abgeschossen. Das Profil verlief W-E und kreuzt die Spreizungsachse in einem Bereich, welcher im Schnitt ca. 500-1000 m tiefer ist als die nördlich und südlich gelegenen Segmente. Die westliche Rückenschulter zeigt eine domartige Struktur. Hier wurde während eines Tauchgangs mit dem französischen Unterseeboot *Nautile* u.a. Unterkrusten- und Mantelgesteine beobachtet. Bei der domartigen Struktur handelt es sich somit um einen sog. ozeanischen „Core Complex". Diese Strukturen treten dort auf, wo die Plattendivergenz zum Teil durch amagmatische Extension getragen wird. Entsprechend tektonisch dominierte Spreizung des Meeresbodens führt dazu, dass sich eine sog. „Detachment Fault" bildet, wobei in der von uns untersuchten Struktur im Westen der Spreizungsachse das Liegende der Störung und im Zentraltal und im Osten der Spreizungsachse das Hangende aufgeschlossen ist. Die seismischen Daten stützen die Vorstellung, dass die Lithologien der beiden Rückenflanken unterschiedlich sind. Hohe seismische Geschwindigkeiten an der westlichen Schulter stützen die Vorstellung, dass hier gabbroide Unterkrustengesteine sehr nahe am Meeresboden vorkommen, während die östliche Flanke eine für ozeanische Kruste typische Geschwindigkeitsabfolge zeigt. Unsere seismische Studie ist die erste, welche die konjugierten Flanken eines entsprechenden Störungssystems abbilden konnte. Darüber hinaus konnten wir erstmalig Weitwinkelreflexionen von der Krusten/Mantelgrenze unterhalb eines „Core Complexes" beobachten. Das Phänomen deutet darauf hin, dass trotz der Ausbildung einer Detachmentstörung magmatische Akkretion stattfindet.