Lastarria Vulkankomplex: Deformationsmessung mit InSAR und Seismizität

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Das Lazufre Vulkanfeld ist Teil des Altiplano-Puna-Plateau in den Zentralanden. Es entstand durch die Subduktion der Nazca Platte unter der Südamerikanischen Platte.

Die Lazufre Vulkanregion zeichnet sich durch eine großflächige (ca. 2000 km²) Hebungszone aus, die mittels Radar-Interferometrie (InSAR) seit etwa 1997 gemessen wurden. Die großräumige Deformation erreicht etwa 2 bis 3 cm pro Jahr und wird von einer lokalen Deformation mit zusätzlich ca. einem cm pro Jahr am Lastarria überlagert. Der Lastarria ist ein 5700 Meter hoher Vulkankomplex am Nordrand der Lazufre Region und zeichnet sich durch massive Schwefel-Entgasungen in Kraternähe und regelmäßige Mikrobeben aus. Inversionsrechnungen lassen die Tiefe der großräumigen Deformationsquelle bei etwa 8 bis 12 Kilometern und jene der lokalen Lastarria Anomalie bei unter einem km Tiefe simulieren.

In Zusammenarbeit der Universität Chile in Santiago, der Universität Hamburg und des Geoforschungszentrum in Potsdam (GFZ) wurde ein Netz von 18 Seismometern von Anfang Februar bis Ende März 2008 installiert. Aufgabe war die Aufzeichnung von Mikrobeben am Lastarria und Lazufre, mit dem Ziel zu prüfen, inwiefern lokale Erdbeben die Deformationsanomalie am Lastarria begleiten.

Einhundertneunzig Erdbeben wurden am Lastarria mit Hyposat lokalisiert und mit hypoDD relativ relokalisiert. Die Erdbeben liegen überwiegend in einer Tiefe von 4 bis 5 Kilometern unterhalb des Kraters und befinden sich im Bereich der kleinräumigen Deformationsanomalie. Damit liegen diese Erdbeben deutlich tiefer, als die durch InSAR-Daten vorgeschlagene lokale Deformationsquelle (<1 km). Eine mögliche Erklärung dieser Diskrepanz könnte eine vertikal elongierte Quellregion in diesem Bereich oder gar zwei getrennte Reservoire liefern. Eine grundsätzlich prolate (zigarrenförmige) Geometrie könnte bruchspröde Prozesse in der Tiefe und eine geothermische (aseismische) Druckquelle in flacher Tiefe erklären, insbesondere da Modelle von Deformationsdaten bekanntermaßen lediglich das Dach von Deformationsquellen darstellen. Somit eignet sich die Kombination aus seismischen und InSAR Daten, um das Verständnis der Quellregion und damit des Plumbingsystems von Lastarria zu verbessern.

In der Präsentation werden die seismologischen Ergebnisse und mögliche alternative Interpretationen der Deformationsanomalie am Lastarria diskutiert.

Microseismic Monitoring of the Marmara Seismic Gap, NW Turkey

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The North Anatolian Fault Zone (NAFZ) below the Sea of Marmara represents a ‘seismic gap’ where a major earthquake is expected to occur in the near future. The Marmara segment of the NAFZ is located between the 1912 Ganos and 1999 Izmit ruptures and is the only segment that has not ruptured since 1766. To monitor the microseismic activity at the main fault branch offshore of Istanbul below the Cinarcik Basin a permanent seismic network (PIRES) was installed in 2006 on the Princes Islands, at a few kilometers distance to the main fault branch. PIRES recordings are combined with data from local permanent stations of the Turkish network and the ARNET seismic network on the Armutlu peninsula in order to get the best available azimuthal control for the target area. We obtain a well-resolved hypocenter catalog of microseismicity allowing us to discriminate seismically active from inactive fault patches along the eastern part of the Marmara seismic gap. The results show that the seismicity generally tends to cluster slightly off the main fault, probably along splay faults, with a well-defined internal spatiotemporal migration. This probably means that the main fault is locked and the slip is transferred to secondary structures which might be due to the major NAFZ branch approaching a late stage of the seismic cycle. Furthermore, PIRES recordings are also used for characterization and pre-selection of borehole locations in the frame of the ICDP-GONAF project aiming at installing a downhole geophysical observatory throughout the eastern Marmara region.

Automated determination of P-wave polarization at GRSN

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Body wave traveltimes are often analyzed for the investigation of crustal and upper mantle structure. In addition, P-wave polarization may yield valuable information on lateral heterogeneity and anisotropy close to the recording station. However, a large number of recordings has to be studied to identify contaminations by noise and to study the dependence of the polarization attributes as a function of backazimuth and epicentral distance. Over the last about 18 month I have developed tools for the automatic determination of P-wave polarization attributes. The incidence angle, the azimuthal deviation as well as the linearity may be automatically determined in different frequency ranges. The tools have been applied to 20 years of recordings at the Gräfenberg Array (Germany). These tests showed (1) that the tools yield robust estimates of the polarization parameters including quality measures if high quality data for more than about 5 years are available. (2) Misorientations of the sensors may be detected. (3) Incidence angles as well as azimuthal deviations of P-waves vary with frequency. (4) The azimuthal deviations are mainly a function of the backazimuth. (5) Fast propagation directions of P-waves may be determined by harmonic analysis of the azimuthal deviations as a function of backazimuth. We applied harmonic analysis to the azimuthal deviations measured at each station of the German Regional Seismic Network at different frequency bands, to extract the dependence on the events backazimuth. It has been possible to retrieve the amplitude of the 180° periodicity term representing the anisotropy of the local structure, assuming an horizontal hexagonal symmetry axis for the anisotropy. The estimated fast direction for the 180° periodicity term in the Gräfenberg array is of (15± 10)°.

The Ahar-Varzaghan twin earthquakes (M_w 6.5 and M_w 6.2) of August 11^{th}, 2012, Iran

The northwestern region of Iran constitutes a transition zone. To the southeast the Arabian indenter tectonics strongly influences the active deformation of the region. In contrast, the westwards extrusion of the Anatolian plate to the west and the subduction tectonics under the Greater Caucasus and the Apsheron-Balkhan sill to the north are also affecting this region. The seismicity in the northwest of Iran is mainly focused on the NW-SE striking North Tabriz Fault (NTF), which has a right-lateral strike-slip character. In the north of the NTF almost no earthquakes occurred during the last 10 years ($M \geq 2.5$, catalogue of the Iranian Seismological Center - IRSC).

The more surprising have been the devastating twin events on August 11^{th}, 2012 (M_w 6.5 and M_w 6.2) about 50 km north of the NTF, in an area, where neither historical nor instrumental catalogues show relevant seismic activity. Both earthquakes happened within eleven minutes. They produced a surface rupture of almost 20 km length striking about 95° with a vertical and horizontal displacement of 15 and 70 cm, respectively. Here, we present full moment tensor solutions of the two mainshocks and selected larger aftershocks. The first mainshock occurred at a depth of 18 km showing a pure right-lateral strike-slip mechanism. The second mainshock was to some extent shallower with 10 km and shows an oblique thrust mechanism. In general, the studied aftershocks show either pure strike-slip or oblique thrust mechanisms, with the thrusts being slightly shallower than the strike-slips. Additionally, we show the aftershock distribution ($M \geq 2.5$) and give a preliminary interpretation of the seismotectonics of these events.

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Tracing the influence of the Trans-European Suture Zone into the mantle transition zone

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A temporary seismic network of about 200 stations, both broad-band and short-period, was installed between 2006 and 2008 in central Europe within the framework of the international PASSEQ (PASive Seismic Experiment in the Trans-European Suture Zone) project. This network offers unprecedented station coverage across the the Trans-European Suture Zone (TESZ), the boundary between the East European Craton and adjacent Phanerozoic Europe, in Poland and Lithuania. Among the issues that can be addressed with these data is the question of how the craton with its thick lithospheric root influences the thermal structure of the surrounding mantle. We use depth variations in the mantle transition zone (MTZ) discontinuities as derived from P-receiver functions as indicators for MTZ temperature anomalies. By using additional data from permanent national and regional networks as well as other temporary broad-band deployments, 479 stations in total, we are able to map the MTZ discontinuities over a large part of central Europe.

We observe significantly shorter travel times for conversions from both MTZ discontinuities within the craton, caused by the high velocities of the cratonic root. By contrast, the differential travel time across the MTZ is normal to only slightly raised. This implies that any insulating effect of the cratonic keel does not reach the MTZ. In contrast to earlier observations in Siberia, we do not find any trace of a discontinuity at 520 km depth.

Within most of covered Phanerozoic Europe, the MTZ differential travel time is remarkably uniform and in agreement with standard Earth models. No widespread thermal effects of the various episodes of Caledonian and Variscan subduction that took place during the amalgamation of the continent remain. Only more recent tectonic events, related to Alpine subduction and Quarternary volcanism in the Eifel area, can be traced. Similar to previous results from tomographic as well as receiver function studies, we find a pronounced deepening of the 660 km discontinuity along the western Carpathian arc, which has been interpreted as indication of cold material, i.e. the subducted lithosphere of the Alpine Tethys, pooled on top of the 660. Besides, we find a region where travel times for both P410s and P660s are reduced by about 1s beneath the central Austrian Alps, pointing to increased velocities in the mantle above. The location of this anomaly correlates with the region where a high-velocity, sub-vertical slab has been mapped tomographically down to the MTZ. Beneath the Eifel region, our data show a elongated region along 7^o E with a delay of 1 s to 2.5 s in P410s, similar to previous receiver function observations. In contrast, the geologically comparable region of the Bohemian Massif shows no indication of thermal variations in the MTZ.

While the East European craton shows no distinct imprint into the MTZ, we discover the signature of the TESZ in the MTZ in the form of a linear region of about 350 km width with a 1.5 s increase in differential travel time, which could be caused by high water content or decreased temperature. Taking into account results of recent S-wave tomographies, raised water content in the MTZ cannot be the main cause for this observation. Accordingly, we explain the increase, equivalent to a 15 km thicker MTZ, by a temperature decrease of about 80 K. Two possible explanations for this temperature reduction are either a remnant of subducting lithosphere that got stuck in the MTZ, or an indication of downwelling due to small-scale, edge-driven convection caused by the contrast in lithospheric thickness across the TESZ. Any subducted lithosphere found in the MTZ at this location is unlikely to be related to Variscan subduction along the TESZ, though, as Eurasia has moved significantly northward since the Variscan orogeny. Thus, while any insulating effect of the cratonic lithosphere does not extend into the MTZ, it might still influence the thermal regime and geodyanmics at that depth by causing edge-driven convection.

The Character of the Core-Mantle Boundary: A systematic study using PcP

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Liquid iron alloy from the outer core possibly interacts with the solid silicate-rich lower mantle. Here we investigate the influence on PcP, i.e. the P-wave reflected at the core-mantle boundary. If the core-mantle-boundary is not a sharp discontinuity, this becomes apparent in the waveform and amplitude of PcP. Iron-silicate mixing would lead to regions of partial melting with higher density which in turn reduces the velocity of seismic waves.

On the basis of the calculation and interpretation of short-period synthetic seismograms a model space is evaluated for this ultra-low velocity zones (ULVZs). The goal is to analyse the behavior of PcP between 10° and 40° source distance for such models using different velocity and density configurations. Furthermore, the resolution limits of seismic data are discussed. The influence of the assumed layer thickness, dominant source frequency and ULVZ topography are analysed. The Gräfenberg and NORSAR arrays are then used to investigate PcP from deep earthquakes and nuclear explosions.

The seismic resolution of an ULVZ is limited both for velocity and density contrasts and layer thicknesses. Even a very thin global core-mantle transition zone (CMTZ), rather than a discrete boundary and also with strong impedance contrasts, seems possible: If no precursor is observable but the $\mathrm{PcP}^{model}/\mathrm{PcP}^{smooth}$ amplitude reduction amounts to more than 10%, a very thin ULVZ of 5 km with a first-order discontinuity may exist. Otherwise, if amplitude reductions of less than 10% are obtained, this could indicate either a moderate, thin ULVZ or a graded CMTZ.

Synthetic computations reveal notable amplitude variations as function of the distance and the impedance contrasts. Thereby a primary density effect in the very steep-angle range and a pronounced velocity dependency in the wide-angle region can be predicted. In view of the modeled findings, there is evidence for a 10 to 15 km thick ULVZ 600 km east of Moscow with a NW-SE extension of about 200 km. Here a single specific assumption about the velocity and density anomaly is not possible. This is in agreement with the synthetic results in which various models create similar amplitude-waveform characteristics. For example, a ULVZ model with contrasts of -5% V_P, -15% V_S and +5% density explain the measured PcP amplitudes. Moreover, below the SW Finland and NNW of the Caspian Sea a CMB topography can be assumed. The amplitude measurements indicate a wavelength of 200 km and a height of 1 km, previously also shown in the study by Kampfmann and Müller (1989).

Better constraints might be provided by a joined analysis of seismological data, mineralogical experiments and geodynamic modeling.

Bodenschwinggeschwindigkeiten aufgrund der Mikroseismizität im Bereich Landau / Südpfalz

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Der Forschungsverbund MAGS soll Konzepte zur Begrenzung der **M**ikroseismischen **A**ktivität bei der energetischen Nutzung **G**eothermischer **S**ysteme im tiefen (> 2km) Untergrund erarbeiten. Das Geophysikalische Institut des KIT ist mit der Durchführung des Einzelprojektes (EP) 1 - Quantifizierung und Charakterisierung des induzierten seismischen Volumens im Bereich Landau / Südpfalz – beteiligt. Im Umfeld des Geothermie-Kraftwerks in Landau sind im Sommer und Herbst 2009 deutlich spürbare Erdbeben aufgetreten (max. Intensität V; max. M_L 2,7). Diese Ereignisse werden mit dem Kraftwerksbetrieb in Verbindung gebracht und haben in der Öffentlichkeit bereits eine generelle Skepsis gegenüber der tiefen Geothermie ausgelöst.

Der bestehende seismologische Datensatz aus der Südpfalz wird durch MAGS-EP1 erweitert und bzgl. der Mikroseismizität ausgewertet. Hierzu werden seit 2009 Messungen mit Stationen des Karlsruher BreitBand Array (KABBA) in einem Umkreis von 10 km um Landau durchgeführt. Gegenwärtig erfolgt die automatisierte Detektion bislang unbekannter mikroseismischer Ereignisse und deren Lokalisierung mit diesem Datensatz. Begleitend werden die aufgetretenen maximalen Bodenschwinggeschwindigkeiten und deren räumliche Verteilung bestimmt. Diese Untersuchung ist für die Beurteilung der Wahrscheinlichkeit von Gebäudeschäden (Anhaltswert nach DIN 4150: 5 mm/s) und für die Bestimmung einer Magnituden-Schwelle bzgl. der Spürbarkeit der seismischen Ereignisse (Anhaltswert nach DIN 4150: 0,14 mm/s) in der Südpfalz von besonderer Bedeutung und großem öffentlichen Interesse.

In diesem Beitrag werden die aktuellen Zwischenergebnisse dieser Untersuchung vorgestellt. Es konnten über 30 Ereignisse (Tiefenlage 2-5 km) mit Magnituden (ML) zwischen 0,7 und 2,7 mit Epizentren im Gemeindegebiet Landau ausgewertet werden. Die bislang beobachteten maximalen Bodenschwinggeschwindigkeiten haben den Anhaltswert für mögliche Gebäudeschäden bislang nicht überschritten, aber für die stärksten Ereignisse mit ML 2,4 (~5 mm/s) und 2,7 (~4,6 mm/s) knapp bzw. nahezu erreicht. Somit muss davon ausgegangen werden, dass bei Ereignissen ab ML 2,4 im Gemeindegebiet Landau die maximale Bodenschwinggeschwindigkeit den Anhaltswert für mögliche Gebäudeschäden lokal überschreiten könnte. Der Anhaltswert für die Spürbarkeit von Bodenbewegungen (0,14 mm/s) wurde im Gemeindegebiet Landau regelmäßig ab einer Magnitude von ML 1,3 überschritten.

Bestimmung der Krustenmächtigkeit und intrakrustaler Strukturen im Gebiet des Rwenzori-Gebirges in Ostafrika mittels P-Receiver-Functions

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Das Rwenzori-Gebirge, welches entlang der Grenze der Demokratischen Republik Kongo und Uganda verläuft, befindet sich im Albertine-Rift, dem westlichen Ast des Ostafrikanischen Riftsystems (EARS). Das Gebirge ist über 5 km hoch und erstreckt sich über eine Fläche von etwa 120 x 50 km. Interessant aufgrund seiner ungewöhnlichen Lage inmitten des Grabenbruchs, wird das Gebirge von zwei Riftsegmenten umschlossen. Datengrundlage für die Untersuchungen in der Rwenzori-Region ist ein temporäres, seismologisches Netzwerk gewesen, das im Umfang von 33 Breitbandstationen zwischen September 2009 und August 2011 von der RiftLink-Arbeitsgruppe der Universität Frankfurt betrieben worden ist. Mit Hilfe der Daten soll die Moho-Tiefenvariation vom Rwenzori-Gebirge über das Rift bis hin zu den Riftschultern untersucht und ein Vergleich der Krustenmächtigkeit zwischen der östlichen und westlichen Riftschulter angestellt werden. Desweiteren soll die Kruste auf intrakrustale Strukturen untersucht werden, um das Gesamtbild in der Rwenzori-Region zu erweitern und lokale Unterschiede im Aufbau der Kruste festzustellen. Unter der Verwendung von P-Receiver-Functions, deren ursprüngliche Wellensignale auf einfache Spikes, konvertierten Signals reduziert worden sind, lassen sich die konvertierten und multiplen Phasen von seismischen Grenzschichten, wie der Mohorovičić-Diskontinuität, bestimmen. Mit Hilfe des Stapelungsalgorithmus der Zhu und Kanamori-Methode (2000) lassen sich die Amplitudenwerte der P-Receiver-Functions zu den theoretischen Differenzlaufzeiten der konvertierten bzw. multiplen Phasen Ps, PpPs und PpSs aufsummieren und ein Amplituden-Maximum für eine gemeinsame seismische Grenzschicht bestimmen. Die damit bestimmten Krustenmächtigkeiten in der Rwenzori-Region zeigen signifikante Variationen. Im Bereich der Riftschultern variiert die Krustenmächtigkeit zwischen 31 und 39 km. Innerhalb des Rifts und auch unterhalb des Rwenzori-Gebirges dünnt sich die Kruste auf bis zu 25 km aus. Zusätzlich zeigen die Daten lokale Diskontinuitäten und eine Niedriggeschwindigkeitszone im Edward-Riftsegment.

Implications of ambient wave field properties for noise-based monitoring and imaging

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We present results from an extensive analysis of the high-frequency (1-10 Hz) ambient seismic wave field recorded around 1 km depth by the vertical array of the Taiwan Chelungpu-fault Drilling Project (TCDP). Multiple processing techniques (spectral analysis, spectral ratios, beamforming, correlation-based polarization analysis) targeted at wave field properties reveal the coexistence of the scattering and ballistic propagation regime. The latter dominates the records, due to the proximity of the recording site to the continuously acting source process associated with anthropogenic activity. We discuss implications of the wave field anatomy on properties of noise correlation functions, and consequences for monitoring subsurface velocity changes. Analysis of a 2-year period shows a seasonal signal associated with local weather patterns; precipitation-induced velocity changes on two different time scales allow estimates of hydro-mechanical properties, and of the hydrologic loading consisting of poroelastic and elastic deformations.

The TCDP example is complemented by results from an application of (microseism) noise-based techniques to image structural properties of the San Jacinto fault zone (SJFZ) area, southern California. The proximity of the study area to constant near-coastal microseism excitation similarly prevents evolution of the wave field towards a more diffuse and isotropic propagation regime. This observation is compatible with independent estimates of the Rayleigh wave scattering mean free path derived from a regional high-resolution tomographic image. Surface wave arrivals in correlation functions from a regional network are analyzed to image a velocity contrast across the SJFZ in the Anza region at shallow depth. We show that the amplitude decay pattern is governed by anisotropic noise propagating directions, and discuss strategies to mitigate this artifact for robust attenuation estimates.

High-precision earthquake locations in Switzerland using regional secondary arrivals in a 3D velocity model

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Accurate earthquake locations, and in particular their focal depths, are crucial for many seismological studies. For example, the distribution of earthquakes in the continental lithosphere provides important information on its mechanical strength and rheology. The distribution of seismological stations at the surface and earthquakes at depth often leads to the ill-posed situation that focal depth is poorly constrained. The use of secondary phases, being either S-wave arrivals or reflected phases, can improve this situation but they come at the cost to introduce the dependency of a new velocity model (S-waves) or to compute travel times for reflected phases in complex and heterogeneous media. In this study we present a new approach to relocate earthquakes in the greater western Alpine region using the main crustal phases (Pg, Pn, PmP) that takes advantage of recent developments in P-wave velocity models and modeling of the Moho topography in the region, as well as the ability to track reflected and refracted phases in three-dimensional (3D) heterogeneous media. Our approach includes a new 3D P-wave velocity model that combines a first order Moho discontinuity based on local earthquake tomography (LET) and controlled-source seismology (CSS) information, and 3D seismic velocity information based on LET. Travel times for the main crustal phases (Pg, Pn, PmP) are computed using a fast marching method. We use a non-linear, probabilistic approach to relocate earthquakes that has been extended to include the use of secondary phases. We validate our approach using synthetic data, which were computed for a real earthquake and different combinations of available phases (Pg, Pn, PmP). We also applied our approach to relocate four selected earthquakes, for which independent information (ground truth information) on their focal depths exist. Our results demonstrate that the precision and accuracy of focal depth estimates can be greatly improved if secondary phases are used. This gain is a combined effect of an improved range of take-off angles and the use of differential travel times between first and secondary arriving phases. Our results also show that reliable information on the Moho depth is crucial to obtain accurate focal depths if Pn or PmP phases are used in the relocation process. Finally, our approach demonstrates that proper identification of the main crustal phases in combination with an appropriate model parameterization in the forward solver will improve earthquake locations.

Analyse und Modellierung seismischer Anisotropie in der Subduktionszone der Zentralanden

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Die Anden entlang der westlichen Küste Südamerikas werden durch die Konvergenzzone der abtauchenden Nazca Platte unter die südamerikanische Platte geformt. Wir untersuchen seismische Daten, welche im Rahmen des ReFuCA-Projekts durch das GFZ Potsdam im Zeitraum von März 2002 bis Januar 2004 erhoben wurden. Die Messstationen waren entlang eines Profils bestehend aus 59 Seismometern mit einem mittleren Abstand von 10 km angeordnet. Dieses erstreckte sich von der chilenischen Küste bei ca. 70° W bis etwa 64,5° W in Bolivien etwa auf Höhe des 21. Breitengrades. In unserer Studie haben wir die seismische Anisotropie im Messgebiet anhand von SKS-Phasen und lokalen Ereignissen analysiert. Neben der herkömmlichen Splitting-Analyse der Einzelbeben wurde auch das Jointsplitting-Verfahren für mehrere Events simultan angewendet. Die Ergebnisse aus den beiden Analysen zeigen eine weitgehende Übereinstimmung der bevorzugten Ausrichtung der schnellen Achse. Im westlichen Teil des Profils liegt diese parallel zur Bewegungsrichtung der abtauchenden Nazca-Platte (Ost-West). Im östlichen Teil des Profils beobachten wir hingegen eine überwiegende Ausrichtung in Nord-Süd-Richtung. Im Bereich um 67° W stimmt die Ausrichtung der schnellen Achse sehr gut mit der Orientierung der Uyuni-Kenayani-Störungszone überein. Es ergeben sich Verzögerungszeiten von maximal 1,2 s.

Zur Erklärung der Beobachtungen führen wir eine FD-Modellierung durch. Mit dieser werden die Effekte verschiedener anisotroper Schichten wie z.B. des Slabs, der kontinentalen Kruste oder des Mantelkeils unabhängig voneinander untersucht. Durch die Kombination mehrerer anisotroper Schichten unter Annahme realistischer Parameter lassen sich die beobachteten Splittingergebnisse der teleseismischen Ereignisse gut erklären. Hierzu wurde eine Reihe unterschiedlichster Modelle berechnet und verglichen. Zusätzliche Informationen bezüglich der Parametereinstellung lieferte die Auswertung lokaler Ereignisse aus dem Slab.

Untersuchung der zeitlichen Variation der seismischen Geschwindigkeit und Trennung von intrinsischer Dämpfung und Streudämpfung anhand von Codawellen

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Einleitung

Im Rahmen des Forschungsprojektes „Probing of Intra-continental magmatic activity: drilling the Eger Rift – International Continental Scientific Drilling Program” (PIER-ICDP) werden an der BGR Codamethoden verwendet, um zeitliche Veränderungen der seismischen Geschwindigkeit und die Dämpfungseigenschaften in der Kruste des Schwarmerdbebengebietes Westböhmen/Vogtland während der Schwarmbeben im Oktober 2008 zu untersuchen.

Codawelleninterferometrie (CWI)

Die Idee ist, dass durch aufsteigende Fluide während der Schwarmbeben die seismische Geschwindigkeit in der Quellregion verringert wird. Insgesamt 285 von der BGR lokalisierte Erdbeben mit Magnituden ml größer als 1.4 werden mit CWI untersucht.

Als erster Schritt werden Erdbebendubletten (Erdbeben mit ähnlichen Wellenformen) ausgewählt, so dass von einem Abstand der Hypozentren von weniger als einem Viertel der seismischen Wellenlänge und ähnlicher Abstrahlcharakteristik beider Beben ausgegangen werden kann. Mittels CWI wird bei den gefundenen Dubletten die zeitliche Verschiebung der Codawellenformen in einem gleitenden Zeitfenster gegeneinander bestimmt. An die ermittelten Verschiebungszeiten des gleitenden Zeitfensters wird eine Regressionsgerade angepasst und deren Steigung ” t/t bestimmt. Für die relative Geschwindigkeitsänderung gilt dann ” v/v = -” t/t.

Es lassen sich relative Geschwindigkeitsänderungen von bis zu 0.12 % beobachten. Bei vergleichbaren Erdbebenschwärmen in Japan sind relative seismische Geschwindigkeitsänderungen von 0.3 % bis 1.5 % nachgewiesen worden (Maede et al., 2010). Dies wirft die Frage auf, ob sich die Beben erzeugenden Mechanismen im Vogtland von denen in Japan unterscheiden.

Energietransfertheorie

Für eine geologische Interpretation der Kruste des Schwarmbebengebiets liefert die Energietransfertheorie Informationen darüber, welche Art von Dämpfungsmechanismus dominiert. Wir benutzen die Energietransfertheorie, um intrinsische Absorption, also die Umwandlung seismischer Energie in Wärme, und durch Heterogenitäten verursachte Streudämpfung im Untersuchungsgebiet zu trennen. Die Seismogramme werden mit 7 unterschiedlichen Bandpässen gefiltert, mit Mittenfrequenzen von 0.375, 0.75, 1.5, 3, 6, 12 und 24 Hz. Für alle Frequenzbänder werden die Drei-Komponenten-Einhüllenden der S-Coda berechnet und geglättet. Die Einhüllenden entsprechen der beobachteten Energiedichte und können mit theoretischen Energiedichten verglichen werden. Wir benutzten die 18 stärksten Ereignisse des Erdbebenschwarms 2008 mit Magnituden ml von 3.1 bis 4.2. Nach der Auswahl der Erdbeben und dem Anpassen der theoretischen Energiedichten erhalten wir Parameter für Streudämpfung und intrinsischer Dämpfung als Funktion der Frequenzbänder.

Typischerweise hat die intrinsische Dämpfung einen stärkeren Effekt als die Streudämpfung. Die mittlere freie Weglänge liegt bei ca. 100 bis 600 km und nimmt mit steigender Frequenz ab. Die Absorptionslänge liegt bei ca. 60 bis 250 km und nimmt grob proportional zur Frequenz ab, was mit einem frequenzunabhängigen Q-Wert korrespondiert. Dies Ergebnis stimmt gut mit Messungen für ganz Deutschland überein (e.g. Sens-Schönfelder und Wegler, 2006).

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Simulation of seismic wave propagation for reconnaissance in mechanized tunnelling

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During mechanized tunnelling, there is a complex interaction chain of the involved components. For example, on one hand the machine influences the surrounding ground during excavation, on the other hand supporting measures are needed acting on the ground. Furthermore, the different soil conditions are influencing the wearing of tools, the speed of the excavation and the safety of the construction site. In order to get information about the ground along the tunnel track, one can use seismic imaging.

To get a better understanding of seismic wave propagation for a tunnel environment, we want to perform numerical simulations. For that, we use the spectral element method (SEM) and the nodal discontinuous galerkin method (NDG). In both methods, elements are the basis to discretize the domain of interest for performing high order elastodynamic simulations. The SEM is a fast and widely used method but the biggest drawback is it's limitation to hexahedral elements. For complex heterogeneous models with a tunnel included, it is a better choice to use the NDG, which needs more computation time but can be adapted to tetrahedral elements.

Using this technique, we can perform high resolution simulations of waves initialized by a single force acting either on the front face or the side face of the tunnel. The aim is to produce waves that travel mainly in the direction of the tunnel track and to get as much information as possible from the backscattered part of the wave field.

Caprese Michelangelo: Natural and induced seismicity near the Alto Tiberina Fault (Italy).

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Abstract:

The Northern and Central Apennines are characterized by intense seismic activity. During the last millennium, merely in the Umbria-Marche Region several damaging earthquakes were recorded.

During the last 20 years, three 5.6<M<6.0 earthquakes occurred on steep SW-dipping normal faults, located at the eastern border of the Apenninic sedimentary basin, called Upper Tiber Valley (UTV). However, the western side of the UTV is characterized by the presence of a NE-dipping low-angle normal fault - the so called "Alto Tiberina Fault" (ATF), which up to now has never been struck by larger historical events. Its high microseismic activity (Piccinini et al., 2003) and GPS-measurements (D'Agostino et al. 2001) suggests a significant seismogenic potential.

Our study area focuses to the area of Caprese Michelangelo, situated at the north-western border of the UTV basin and the northern end of the ATF. This area is characterized by the occurrence of weak and moderate seismicity, including earthquakes swarms, and strong natural diffuse CO2 degassing.

Furthermore, Caprese Michelangelo is also adjacent to a large artificial lake and a huge CO2 reservoir found beneath a sealing layer at a depth of about 3 km b.s.l.

Commercial production of these reservoir gases (up to 5 tons/hour) by a private company started on July 2011.

In the framework of a bilateral cooperation between INGV Arezzo and the Institute of Geophysics of the University of Hamburg a local seismic small aperture array of 8 broadband stations was operating near the reservoir from July 2010 to September 2011

The aim of this work is to analyze the recorded seismic events before and after the commercial gas production, and to evaluate the influence of the fluid extraction on the local seismicity, in order to define criteria for the distinction of natural and human related seismicity.

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A shear-wave velocity model of the European upper mantle from automated inversion of seismic shear and surface waveforms

C. Legendre, T. Meier, S. Lebedev, W. Friederich and L. Viereck-Götte

Broadband waveforms recorded at stations in Europe and surrounding regions were inverted for shear-wave velocity of the European upper mantle. For events between 1995 and 2007 seismograms were collected from all permanent stations for which data are available via the data centers ORFEUS, GEOFON, ReNaSs and IRIS. In addition, we incorporated data from temporary experiments, including SVEKALAPKO, TOR, Eifel Plume, EGELADOS and other projects. Automated Multimode Inversion of surface and S-wave forms was applied to extract structural information from the seismograms, in the form of linear equations with uncorrelated uncertainties. Successful waveform fits for about 70,000 seismograms yielded over 300,000 independent linear equations that were solved together for a three-dimensional tomographic model.

Resolution of the imaging is particularly high in the mantle lithosphere and asthenosphere. The highest velocities in the mantle lithosphere of the East European Craton are found at about 150 km depth. There are no indications for a large scale deep cratonic root below about 330 km depth. Lateral variations within the cratonic mantle lithosphere are resolved by our model as well. The locations of diamond bearing kimberlites correlate with reduced S-wave velocities in the cratonic mantle lithosphere. This anomaly is present in regions of both Proterozoic and Archean crust, pointing to an alteration of the mantle lithosphere after the formation of the craton. Strong lateral changes in S-wave velocity are found at the western margin of the East European Craton that hint to erosion of cratonic mantle lithosphere beneath the Scandes by hot asthenosphere. The mantle lithosphere beneath Western Europe and between the Tornquist-Teyissere Zone and the Elbe Line shows moderately high velocities and is of an intermediate character, between cratonic lithosphere and the thin lithosphere of central Europe. In central Europe, Caledonian and Variscian sutures are not associated with strong lateral changes in the lithosphere-asthenosphere system. Cenozoic anorogenic intraplate volcanism in central Europe and the Circum Mediterranean is found in regions of shallow asthenosphere and close to sharp gradients in the depth of the lithosphere-asthenosphere boundary. Indications for low-velocity anomalies extending vertically from shallow upper mantle down to the transition zone are found beneath the Massive Central, Sinai, Canary Islands, Iceland, and the Adriatic Sea.

Die Instrumentenantwort:
Ein Vergleich von Beschleunigungsaufnehmer und AE-Sensoren

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Akustische Emissions (AE) Sensoren wurden ursprünglich hauptsächlich in der Materialprüfung eingesetzt. Ein weiteres grosses Anwendungsgebiet sind Deformations-messungen im Labor wie z.B. in der Bruchmechanik. An der Messung von seismischen Ereignissen in der Erdkruste mit AE-Sensoren besteht ein zunehmendes Interesse. Da AE-Sensoren im kHz bis MHz Bereich sensitiv sind, ermöglichen sie die Messung von seismischen Ereignissen im (Sub-)Zentimeter Bereich. Diese sehr kleinen seismischen Ereignisse sind in der hochauflösenden Überwachung in aktiven und stillgelegten Bergwerken und Stollen, sowie für die Grundlagenforschung von grosser Bedeutung.

Im Gegensatz zu anderen Seismometern basieren AE-Sensoren jedoch nicht auf dem Prinzip des Pendels und sind grundsätzlich nicht hinlänglich kalibriert. Es stellt sich die Frage für welche seismologischen Messungen AE Sensoren geeignet sind und wie sich die Instrumentenantwort des Sensors auf seismologische Untersuchungen auswirkt.

Im Rahmen des JAGUARS (Japanese-German Underground Acoustic Emission Research in South Africa) Projektes wurden in der Mponeng Gold Mine in Carletonville, Südafrika AE-Sensoren zusammen mit Beschleunigungsaufnehmern installiert.
Durch Dekonvolution der aufgezeichneten Signale konnten hier die AE-Sensoren relativ zu einem 3-Komponenten Beschleunigsaufnehmer mit bekannter Instrumentenantwort kalibriert werden. Wir stellen hier die Ergebnisse dieser relativen Kalibrierung vor.

Die Ergebnisse spiegeln die Antwortfunktion der AE-Sensoren, welche durch eine Vielzahl von Resonanzfrequenzen geprägt ist, sowie den Ankopplungseffekt wieder. Im analysierten Frequenzbereich von 1 kHz bis 17 kHz wurden drei wesentliche Resonanzfrequenzen bei 2.5 kHz, 6 kHz und 10 kHz identifiziert. Auch die Richtungsabhängigkeit der Sensoren konnte quantifiziert werden und zeigt bei orthogonalem Einfall eine Reduktion von mehr als -10dB.

Es folgt, dass eine unbekannte Antwortfunktion von AE Sensoren auf die Analyse von Herdparametern einen wesentlichen Einfluss haben kann.

Searching for non-volcanic tremor at the North Anatolian Fault Zone: status report

Christina Raub, Marco Bohnhoff

In the last century the North Anatolian Fault Zone (NAFZ) has produced several large earthquakes (M > 7) that propagated westward from Erczincan in eastern Anatolia in 1939 towards the Izmit-Sapanca and the Istanbul-Marmara region in northwestern Turkey where the most recent events occurred in 1999. The Sea of Marmara segment of the NAFZ is the only segment of the fault zone that has not been activated since 1766, currently representing a 'seismic gap'. In 2006 the permanent PIRES (Prince Islands Realtime Earthquake Monitoring System) network has been installed offshore Istanbul to monitor the microseismic activity at the eastern Marmara seismic gap with a low magnitude detection threshold. The fault structure and kinematic setting underneath the Marmara segment, especially in the deep crust, is still not fully understood and due to a lack of geodetic measurements it is unclear if this fault segment is currently locked or creeping. At the San Andreas Fault (SAF) in California and the Alpine Fault (New Zealand), both representing major transform faults like the NAFZ, it was possible to investigate the downdip extension of the fault below the seismogenic layer in the lower crust underneath creeping and locked fault segments through analyzing non-volcanic tremor (NVT). NVT are non-impulsive, low frequency, long duration seismic signals. Such signals have been first observed at several subduction zones, where they are located down-dip of the seismogenic zone of the plate interface and can be related to fluid release during oceanic slab dehydration. The existence or non-existence of NVT at the NAFZ in the Marmara region can have implications for seismic hazard in the broader Istanbul metropolitan region due to the stress variance caused by tremor activity. Furthermore, the analysis of tremor signals could provide unprecedented insights to the deep extension of the fault.

Here, we present first attempts to systematically search for NVT at the NAFZ using continuous seismic data from the PIRES network and from selected stations of the regional KOERI and ARNET networks. We apply two different detection methods. 1) A small aperture array analysis method to detect signals that are coherent across the array and have a relatively constant azimuth and slowness over a certain time period. 2) A spectrogram analysis method to detect signals with low frequency contents and a long duration, followed by a coherency trigger that selects the coherent signals. The detected signals may as well be coherent noise and earthquakes with long duration and low frequency. We discriminate between noise and tremor signals by visual inspection and by applying a short-term-average/long-term-average trigger to automatically eliminate earthquakes from the detection list. Both methods have been successfully tested on tremor waveforms from the SAF and Alpine Fault. So far twelve months of recordings were analyzed. While some examples of detected signals at the NAFZ show long duration -low frequency events, no clear tremor signal has yet been identified throughout the area of investigation.

A 3D Shear Wave Tomography Model of the Upper Mantle below the Southern Scandes

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The present high topography of the Scandinavian Mountains (Scandes) cannot be explained uniquely, because it is far away from active plate boundaries. The main mountain building phase happened during the Caledonian orogeny (~450-420 Ma ago), however today the mountains still reach up to 2600 m altitude and display partly a rough and steep scenery. There are hypotheses that young uplift phases in the Neogene renewed the mountain building, including dynamic processes in the upper mantle. The TopoScandiaDeep collaborative research project (www.geo.uio.no/toposcandiadeep) within the ESF programme TOPO-EUROPE develops an integrated model to explain the evolution of the topography of the Scandes. Here we use teleseismic shear wave recordings from the MAGNUS experiment (Weidle et al., 2010, Seis. Res. Lett.) in order to analyse travel time residuals and to determine a 3-D model with velocity perturbations of the upper mantle underneath the Southern Scandes.

The 6196 crust-corrected relative S-wave residuals were determined for the radial (3337) and transverse (2859) recording components from 128 earthquakes. The maximum relative delay time variation across Southern Norway is about four seconds. The residuals of the two different recording components show a very similar spatial distribution without clear hints for influence by seismic anisotropy. The main residual pattern is a delay time of about 2-3 s for waves that propagate underneath the Southern Scandes. The 3-D model shows that a low S-wave velocity anomaly is present underneath the Southern Scandes down to the mantle transition zone. The main well-resolved anomalies are (I) reduced velocity (-2%) along the Norwegian coast relative to the continental region at 35-180 km depth. (II) Increased velocity (+1.5%) below the Oslo Rift area relative to its surroundings at 35-75 km depth. (III) Increased velocity below the Baltic Shield underneath Sweden compared to the Southern Scandes in Norway. This contrast occurs along an eastward dipping boundary at 35-180 km depth. (IV) The S-wave velocity reduction still is as high as 3% in the lowermost upper mantle, down to at least the 410 km discontinuity. The results are interpreted as structural difference between the thinner lithosphere in the west including the Scandes and the thicker Baltic Shield in the east. Increased temperatures in the upper mantle may decrease the S-wave velocity down to the 410 km discontinuity (which is wrapped downwards as found in receiver function studies). This finding indicates that the present topography of the Southern Scandes is supported at least partly by dynamic mantle processes.

Der Deutsche Geräte-Pool für amphibische Seismologie, mariner Teil (DEPAS-MA): Rückblick und Neuigkeiten

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Der „Deutsche Geräte-Pool für amphibische Seismologie (DEPAS)“ ist ein Pool breitbandiger Seismometer für Langzeiteinsätze an Land und auf dem Meeresboden. Der marine Teil besteht aus 80 Ozeanboden-Seismometern (OBS), welche technisch und organisatorisch vom Alfred-Wegener-Institut Bremerhaven (AWI) betreut werden. In diesem Beitrag wird ein kurzer Rückblick auf das vergangene Jahr gegeben und über den aktuellen Stand berichtet, außerdem werden geplante Entwicklungen vorgestellt.

The Very Broadband Seismic Station TROLL, Antarctica

J. Schweitzer, M. Pirli & M. Roth, NORSAR

Troll is the name of the Norwegian permanent research station in Dronning Maud Land, Antarctica. The research base is located inside the continent, at an elevation of about 1300 m and at a distance of about 230 km from the shelf ice border. In the first week of February 2012, a new very broadband seismic station was installed at TROLL.

Contrary to many other seismic stations inside the Antarctic continent, the new seismic sensor could be installed on bedrock (migmatite), on a hill at about 300 m distance from the main buildings of the Troll research base. A bedrock installation has the advantage that seismic signals are not disturbed by multiples due to the thick Antarctic ice sheet. The equipment consists of a Streckeisen STS-2.5 broadband sensor and a Quanterra Q330HR 26 bit digitizer. All data are transferred in real time via a satellite link to NORSAR for analysis and further distribution.

Until now, the new seismic station is running very stably and first data analysis results will be presented. In particular interesting are the general noise level of the station, the global, regional and local seismicity observed with the station and the very exciting monitoring capabilities of icebergs drifting along the coast of Dronning-Maud Land.

Statusbericht SZO der BGR auf Jahrestagung der AG Seismologie, Bochum, 25.-27.9.
K. Stammler

Zusammenfassung

Stationsbetrieb
Die Stationen des Regionalnetzes wurden wie bisher auch in Zusammenarbeit mit den Universitäten, Landesämtern, dem GFZ und Bundeseinrichtungen betrieben. Neue Standorte sind UBR (Überruh im Allgäu, in Koop. mit Erdbebendienst Südwest), GOR1 (Zentralstation des Netzes Gorleben, Dateneigner: BfS) und RETH (Rethem/Aller, BGR-Station, Installation im Oktober geplant). Erstmalig kommt ein Bohrlochinstrument CMG-3TB der Firma Güralp zum Einsatz (Station GOR1 und RETH). Die Datenqualität des neuen Instruments in GOR1 ist bisher nur teilweise befriedigend, langperiodische Defizite sind möglicherweise zumindest partiell durch die lokalen Gegebenheiten verursacht. Die Datenqualität wird durch Datenbeispiele erläutert.

Datenzentrum
Das seismologische Datenzentrum des BGR nimmt an einer europäischen Initiative zur Homogenisierung des Datenzugriffs mit modernen europäischen Standards (arclink) teil. Dieser verbund soll innerhalb der nächsten Monate aufgebaut werden und mit einem MoU abgesichert werden. Gründungsteilnehmer sind neben der BGR das GFZ Potsdam, der Schweizer Erdbebendienst an der ETH Zürich, aus Italien das INGV, das französische Datenzentrum RESIF und das europäische Datenzentrum ORFEUS in DeBilt/Niederlande. Die Hardware und Software des Datenzentrums wird beständig erneuert und den aktuellen Anforderungen an Ausfallsicherheit angepasst. Weiterhin wird auf Anregung der inneren Revision der BGR ein Qualitätsmanagement eingeführt und Vorgaben der IT-Sicherheit umgesetzt. In diesem Rahmen wird zurzeit ein Testsystem-Umgebung der Datenzentrums-Software des SZO erstellt.

Localisation And Characterisation Of Ocean Microseisms With On- And Offshore Stations In The Barentsshelf Region

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Abstract

Seismic data from the Barentsshelf (west of Bear Island) recorded from fall 2007 until summer 2008 was analysed for its oceanic microseisms characteristics. The analysis was focused on the spectral behavior and the source regions of the recorded microseisms activities. Especially, how the microseisms differ from station to station and how it evolves during that year.

Spectral analysis showed that spectral maxima were in the range of 0.2Hz - 0.3Hz. Comparison between winter and summer spectra showed a slight shift of the maxima by approx. 0.07Hz to higher frequencies. Also the amplitudes in summer were much smaller than in winter. Both effects are caused by the sea waves which have also a frequency shift from winter to summer which is approx. half of the microseisms shift.

The source regions for the microseisms have been detected by correlating the microseismic amplitudes at different frequencies with combined wind waves and swell data in the range from 50°N to 80°N and 50°W to 65°E. The correlation revealed two main source regions. The first one has a north-south-extent from 68°N to 80°N which is between northern Norway and Svalbard. Its average east-west extension varies during the year. In winter it is more east, between 10°E and 50°E. But during spring and summer it moves to the west and has then an east-west extension from 10°W to 30°E. This is a quite local generation area and with correlation coefficients up to 0.77 for correlation windows of 79 days and depending on frequency and station. The second main source region is west to north-west of the British Isles. It has smaller correlation coefficients than the first one and is more active during the summer than the winter.

The relatoinship between R- and Z-component of a Rayleigh wave allows to calculate the azimuth of an incident Rayleigh wave. Thus, this technique allows to home on the microseisms source regions. Comparison with the correlation method shows that in calculated azimuth directions areas with high correlation-coefficients can be found.

Poster über aktuelle Entwicklung des Seismic Handler

Marcus Walther und Klaus Stammler, Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover

Auf dem Poster wird die aktuelle Version 2012a vorgestellt. Die wichtigsten Änderungen betreffen die Simulationsfilter zur Magnitudenbestimmung anhand neuer IASPEI-Regelungen für Wood-Anderson, WWSSN-SP und WWSSN-LP.

Die Version 2012a enthält weiterhin aktualisierte Metadaten für Stationen und Seismometer. Ein Abruf der Informationen über das arclink-Protokoll ist nun möglich.

Für die neue Version SHX steht jetzt eine Entwicklerversion frei zur Verfügung, welche den Großteil der bekannten Kommandos des Seismic Handler abdeckt.

SURFACE WAVE TOMOGRAPHY OF CENTRAL TO NORTHERN EUROPE – FIRST TESTS USING AUTOMATED INTER-STATION DISPERSION MEASUREMENTS

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Broad-band phase velocity curves of fundamental mode surface waves yield information on the isotropic as well as anisotropic structure of the lower crust and the upper mantle. An automated measurement algorithm is applied to direct and coda waveforms of fundamental Rayleigh and Love modes recorded at stations in central and northern Europe.

By this intereferometric method the waveforms recorded at two stations are cross correlated and frequency dependent time windows are applied to the cross correlation function. The dispersion curves of fundamental modes are calculated from the phase of the weighted cross correlation function. Smooth parts of the single event measurements are selected and measurements for a larger number of events are averaged in order to reject or to reduce influences by local scattering, noise, higher modes, off-path propagation, and erroneous response correction.

We have tried to automatize this whole process, including searching for suitable events, download of waveform data, response correction, rotation of the horizontal components, format conversion, single-event measurements, and the determination of the path-average dispersion curves. For about 400 paths in central and northern Europe fundamental mode dispersion curves are determined. Anisotropic phase velocity maps are calculated for periods between 10 seconds to 200 seconds. Lateral changes in isotropic Rayleigh and Love wave velocities along the Trans-European Suture Zone are discussed. Periods with significant anisotropy as well as the lateral extent of anisotropic structures are identified.

The use of direct shear waves in quantifying seismic anisotropy: Reference station technique applied on the Northeastern Tibet

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Using direct shear waves in addition to SKS waves for splitting measurement would be advantageous in splitting measurements since they sample possible anisotropic structures in the upper mantle with an increased range of incidence angles and backazimuths. However, this is rarely done because of the potential contamination of the direct S-waves by source-side anisotropy. To overcome the influence of the source we use a new approach that we call “reference station method”. The method utilizes the observations of direct shear waves from two receiving stations at a station pair, one as a reference station with a well-known SKS splitting parameter and the second one as a target station with unknown splitting parameters. The method depends on maximizing the correlation between these seismic traces at reference and target stations after correcting the reference station for known receiver side anisotropy effect. This algorithm also provides a delay time between both stations which represents the isotropic heterogeneity. This delay time can be used to correct body wave S tomographic images for potential biases due to unmodelled splitting effects. The procedure effectively assumes the same source side anisotropy affecting the two stations for the same seismic event which is reasonable for teleseismic arrivals where two ray paths will be very close in the upper mantle near the source. Synthetic tests performed using various hypothetical anisotropic models show sufficient stability of direct S-based splitting parameters with those obtained from a SKS method even where variability in near surface properties (i.e. thickness and velocity of sediment layer) exists. We also applied the reference station technique to data from the *INDEPTH IV* and *ASCENT* seismic experiments at the northern margin of Tibet. Average splitting parameters, obtained from the analysis of direct shear waves recorded at possible station pairs within a range of interstation distance less than 300 km are mostly similar to the analysis previously carried out using the SKS method. Where differences exist, the resolved shear wave fast polarization estimates from direct S indicate a higher degree of internal consistency for closely spaced stations than those derived from SKS. This is probably due to the much larger number of S waves available for splitting measurements compared to SKS for the same observational period. This and other tests show that the reference station method is robust and has the potential to provide improved splitting measurements for temporary stations operational for too short a time or in locations unfavourably located with regard to SKS. Even where good measurements are available from SKS measurements, the S measurements sample the anisotropic layer with different angles of incidence and at different backazimuths, providing additional constraints on more complicated anisotropic structures such as multi-layer or dipping anisotropy.