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Structural Context of the Great Sumatra-Andaman Islands Earthquake

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Abstract

A new three-dimensional seismic model and relocated regional seismicity are used to illuminate the great Sumatra-Andaman Islands earthquake of December 26, 2004. The earthquake initiated where the incoming Indian Plate lithosphere is warmest and the dip of the Wadati-Benioff zone is least steep along the subduction zone extending from the Andaman Trench to the Java Trench. Anomalously high temperatures are observed in the supra-slab mantle wedge in the Andaman back-arc. The subducting slab is observed along the entire plate boundary to a depth of at least 200 km. These factors contribute to the location of the initiation of rupture, the strength of seismic coupling, the differential rupture speed between the northern and southern segments of the earthquake, and the cause of convergence in the Andaman segment.

1. Introduction

The 26 December 2004 SumatraAndaman earthquake was the third largest instrumentally observed seismic event , with a moment-magnitude of about M = 9.3 [e.g., *Stein and Okal*, 2005, 2007]. This earthquake produced an unprecedented amount of high-quality geophysical data whose analysis provides insight into the generation of the tsunami, the origin of similar earthquakes, and regional tectonics. Numerous studies [e.g., *Ammon et al.*, 2005; *Banerjee et al.*, 2005; *deGroot-Hedlin*, 2005; *Guilbert et al.*, 2005; *Ishii et al.*, 2005; *Lay et al.*, 2005; *Ni et al.*, 2005; *Park et al.*, 2005; *Tolstoy and Bohnenstiehl*, 2005; *Tsai et al.*, 2005; *Vigny et al.*, 2005; *Stein and Okal*, 2007] have demonstrated that the Sumatra earthquake ruptured an area greater than 18000 km^2 along a 1300 km boundary between the Indian Plate and the Burma Microplate (often considered to be part of the greater Eurasian Plate). The earthquake rupture proceeded along two distinct segments with different rupture speeds [e.g., *Bilham*, 2005]. The southern (Sumatran) segment where the rupture originated is characterized by normal rupture speeds and generated most of high-frequency seismic radiation. The northern (Andaman-Nicobar) segment of the rupture, in contrast, released about two-thirds of the total seismic moment [*Stein and Okal*, 2005] and had an unusually slow rupture speed. Another peculiar observation is that, while all previous large (M $>$ 9) earthquakes have occurred in regions where subduction is largely perpendicular to the trench, the present-day plate models and tectonic reconstructions indicate that the nearly oblique incidence of the Indian and Burma plates (Fig. 1A) has occurred west of the Andaman Sea for at least 20 million years [e.g., *Lee and Lawver*, 1995; *Hall*, 1996; *Replumaz et al.*, 2004]. Finally, the Sumatra earthquake has provided a wealth of new information to investigate the conditions needed for a subduction zone to generate a giant tsunamigenic earthquake.

The characteristics of this earthquake can be partially understood in terms of surface observables that have revealed its unusual tectonic setting, including the age-variability of the incoming Indian Plate along its subducting edge (Fig. 1a), the existence of active spreading in the back-arc beneath the Andaman Sea [e.g., *Ortiz and Bilham*, 2003; *Raju et al.*, 2004; *Khan and Chakraborty*, 2005], and anomalously strong strain partitioning [e.g., *McCaffrey et al.*, 2000; *Michel et al.*, 2001; *Socquet et al.*, 2006] in which the oblique Sumatra-Andaman subduction is accommodated by strike-slip motion released along the transform Sumatra and Andaman faults that run nearly parallel to the trench. Better understanding of the earthquake and its consequences, e.g., post-seismic regional stress re-organisation [e.g., *McCloskey et al.*, 2005; *Nalbant et al.*, 2005] and relaxation, will come in part from improved models of the thermal and mechanical structure and depth variability of the subducting slab and the overriding plate. To address this issue we have relocated and reviewed modern and historical seismicity and produced a new shear velocity model of the uppermost mantle constructed using broadband seismic surface waves.

2. Data and methods

To improve knowledge of historical seismicity, we relocated all instrumentally recorded earthquakes in the Andaman Islands region that are well constrained by teleseismic observations using well established methods [e.g., *Engdahl et al.*, 1998; *Engdahl and Villasenor*, 2002] , giving special attention to focal depth. These earthquakes are complete and have been reviewed to magnitude 6.5 for the historical period (pre-1964) and 5.5

for the modern period with a relative location accuracy of about 15 km. Reviewing entails examining the internal consistency of the arrival time data, particularly the depth phases. Observed seismicity portrays the spatial distribution of interslab and intraslab (intermediate-depth) earthquakes in the region and the relationship of this seismicity to regional structures (Figs. 2A-C).

Surface waves provide the most uniform coverage of the region of study and observations of surface wave dispersion strongly constrain shear velocities which are related to temperatures in the uppermost mantle [e.g., *Goes et al.*, 2000; *Shapiro and Ritzwoller*, 2004]. Using information about surface wave phase [e.g., *Trampert and Woodhouse*, 1995; *Ekström et al.*, 1997] and group [e.g., *Ritzwoller and Levshin*, 1998; *Ritzwoller et al.*, 2002] speed dispersion across the region at periods ranging from 15 sec to 150 sec, we estimated a three dimensional (3-D) tomographic model of shear-wave speed in the upper mantle on a $1^\circ \times 1^\circ$ grid. The method involves surface-wave tomography based on finite-frequency sensitivity kernels [*Ritzwoller et al.*, 2002] followed by a Monte-Carlo method [*Shapiro and Ritzwoller*, 2002, 2004] to estimate both shear velocity and temperature in the upper mantle. Plotted here are images of the middle of the ensemble of acceptable models for each variable at each depth. The temperature parameterization [*Shapiro and Ritzwoller*, 2004; *Ritzwoller et al.*, 2004] allows us to estimate the "apparent thermal age" of the oceanic lithosphere that is the age at which a conductively cooling half-space would match the observed lithospheric temperature structure.

3. Discussion

The relocated seismicity and the 3-D model of the seismic (V_s) and thermal structure of the upper mantle shed light on the location of the initiation of rupture in northern Sumatra (red star, Fig. 1A) and may also illuminate why rupture proceeds differently in the southern and northern segments of the fault. These issues are likely to be related to the age and the dip angle of the subducting oceanic plate and to the properties of the supra-slab mantle wedge which may influence seismic coupling along the subduction zone.

Prior to about 40 Ma, India and Australia occupied different plates separated by a spreading center called the Wharton Ridge [e.g., *Weis and Frey*, 1996; *Deplus et al.*, 1998; *Hébert et al.*, 1999]. After ∼40 Ma, Australia rifted from Antarctica, seafloor spreading along the Wharton Ridge ceased, and India and Australia began to move in unison as part of the Australian-Indian Plate. This complex history is apparent in the variation of lithospheric age along the Andaman, Sunda, and Java Trenches (Fig. 1A), with the youngest oceanic lithosphere (Wharton Fossil Spreading Ridge) of about 40 Ma currently being subducted beneath northern Sumatra [*Mueller et al.*, 1997]. Significantly older lithosphere is subducting at both the Andaman and Java trenches. The seismically inferred thermal structure of the incoming Indian Plate represents the plate's tectonic history (Fig. 1B). The young apparent thermal age approximately follows the Wharton Fossil Ridge with the warmest lithosphere lying somewhat to its north. The offset of the apparently youngest (and hence warmest) lithosphere from the Wharton Ridge may be explained by the influence of the Kerguelen plume [*Weis and Frey*, 1996] that caused the delayed thickening of the oceanic lithosphere under the Ninetyeast Ridge. The oceanic lithosphere approaching northern Sumatra (Fig. 2B, profile B-B') is also observed to be thinner than oceanic lithosphere approaching the Andaman and Java Trenches (Fig. 2A,C), and thinner upon subduction as well.

The location of the thermally warmest and thinnest incoming lithosphere is at the Sunda Trench, therefore, which nearly coincides with the initiation of rupture of the Great Sumatra-Andaman Islands earthquake and with its southern "fast" rupture segment. This is probably no coincidence, because the warmer subducting lithosphere near the Wharton Fossil Ridge is more buoyant and the slab dips less steeply (Fig. 2B). The coupling to the overlying plate, therefore, may be stronger than beneath the Andaman and Java trenches. Stronger coupling is also indicated by GPS data in this region [e.g., *Vigny et al.*, 2005]. In addition, the Benioff-Wadati zone in northern Sumatra is less steep than in adjacent areas to the north and south (30° compared with 50° and 40° to the north and south, respectively), consistent with the thermal state of the incoming lithosphere.

In the northern, subducting Andaman segment, characterized by "slow" rupture propagation, much older and less buoyant oceanic lithosphere is subducted at the Andaman trench. The seismic velocities in the back-arc are very slow in this region. This implies that the upper mantle beneath the Andaman Sea is warm, consistent with its interpretation as an extensional basin created by rifting over the past 11 Ma caused by the relative motion of various lithospheric blocks in response to the collision between India and Asia [e.g., *Tapponnier et al.*, 1982; *Raju et al.*, 2004; *Khan and Chakraborty*, 2005]. This combination of the less buoyant subducting plate and the weak (or rather absent) back-arc lithosphere may result in weaker seismic coupling within the Andaman segment than within the more southerly Sunda segment. This may, therefore, contribute to the differences in rupture speed and seismic radiation between these two segments of the Great Sumatra earthquake.

Improved knowledge of seismicity and the thermal structure of the upper mantle also illuminates why a great earthquake occurred at a highly oblique plate boundary. Subducting lithosphere is clearly imaged by surface waves along the entire plate boundary, from the Andaman Trench to the Java trench (Figs. 2A-C, 3) down to at least 200 km depth with well defined Wadati-Benioff zones. This confirms the results from previous regional and global P-wave tomographic models [e.g., *Replumaz et al.*, 2004; *Widiyantoro and Van der Hilst*, 1996; *Hafkenscheid et al.*, 2001] and of a more recent study by *Kennett and Gummins* [2005] showing the trace of subducted oceanic lithosphere at greater depths. Centroid-moment-tensor solutions show that thrust earthquakes are common along the Nicobar-Andaman segment of the subduction zone with nearly east-west compression [e.g., *Rajendran and Gupta*, 1989]. Large historical ($M > 8$) thrust earthquakes have occurred [e.g., *Ortiz and Bilham*, 2003] along this segment and GPS data indicate non-negligible east-west convergence [*Paul et al.*, 2001]. Convergence must, therefore, be occurring and has occurred well into the past along the entire plate boundary, even beneath the most oblique Nicobar-Andaman segment of the plate boundary. This is in striking contrast with the purely transform motion observed in other very oblique segments of subduction zones. An example is the Western Aleutians [*Levin et al.*, 2005] where a slab window is observed beneath the trench along the highly oblique segment of the plate boundary which is devoid of both subducting lithosphere and deep seismicity. We speculate that convergence may be enhanced by the weak Andaman lithosphere responding to slab roll-back.

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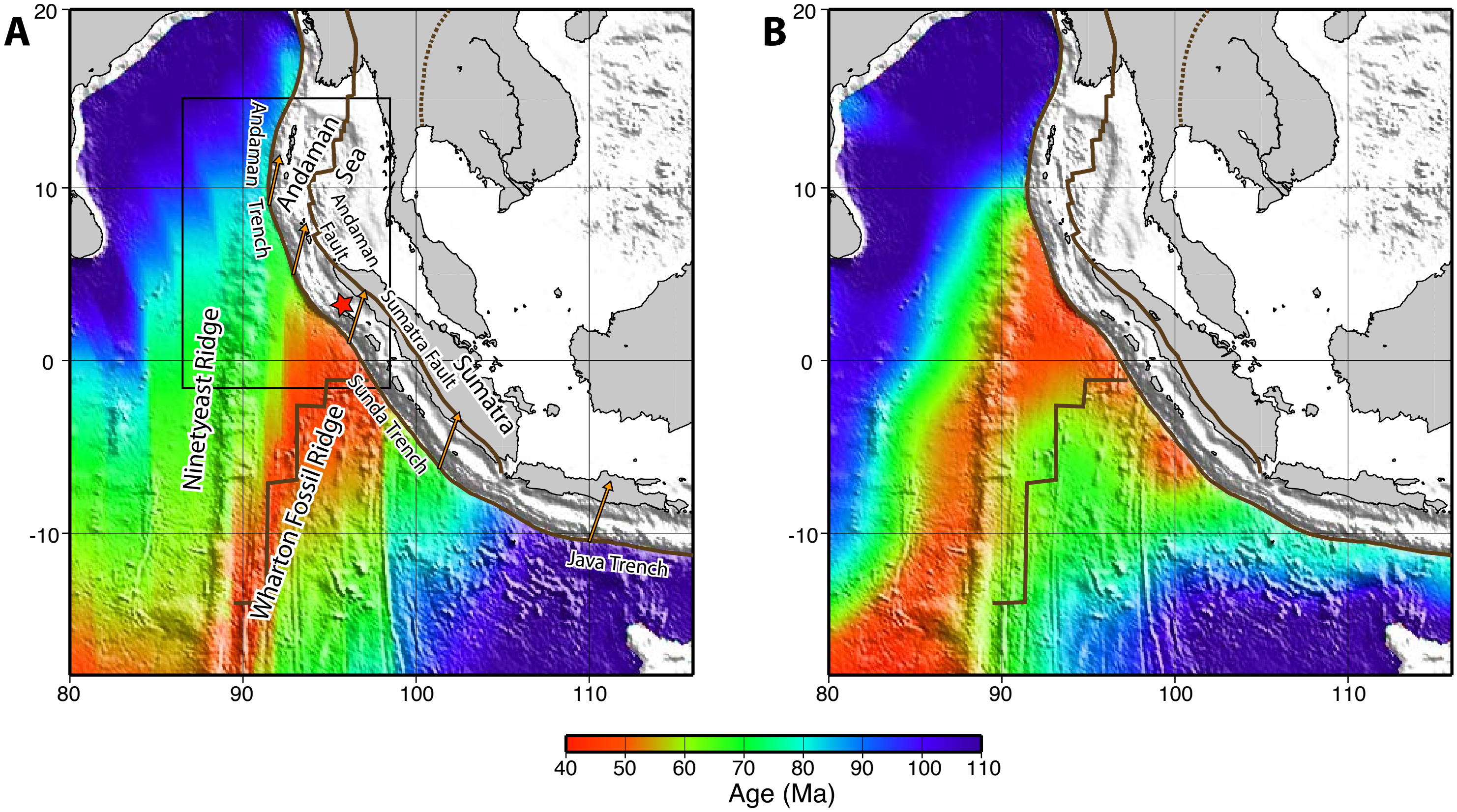
Figure 1. (A) Reference map showing the locations of the principal geographical and geological features discussed in the text. The red star marks the location of the initiation of rupture of the great Sumatra-Andaman earthquake. Brown lines show active and fossil plate boundaries. Arrows show the relative plate motion [*DeMets et al.*, 1994]. The age of the incoming oceanic plate [*Mueller et al.*, 1997] is shown with colors in millions of years. The black rectangular box indicates the region shown in Fig. 3. (B) Distribution of the apparent thermal age which results from the seismic inversion using the thermal parameterization [*Shapiro and Ritzwoller*, 2004; *Ritzwoller et al.*, 2004]. It is defined as the lithospheric age at which apurely conductive temperature profile would most closely resemble the observed thermal structure.

Figure 2. Results of the inversion using the seismic parameterization [*Shapiro and Ritzwoller*, 2002]. (A-C) Vertical cross-sections throughthe shear velocity model. Colors indicate anomalies in S-wave velocity relative to a regional one-dimensional profile. The locationof the trench and the Sumatra and the Andaman Faults are shown with small arrows on top of the cross- sections. Hypocentres of relocated earthquakes within 100 km of the profile plane are shown by circles. Larger white circles indicate hypocenters that were both relocated and reviewed. Dashed lines show the deduced orientation of the Wadati-Benioff zones. (D) and (E) Horizontal cross-sections through the shear velocity model at 50 km and 100 km depths, respectively.

Figure 3. Isosurface representation of the shear velocity model beneath part of northern Sumatra and the Andaman Sea (identified with the black box in Fig. 1), in which the model was laterally smoothed with a gaussian filter ($\sigma = 100km$) to highlight the dominant large-scale features. The blue surface (+1.2%) represents the high seismic velocity oceanic lithosphere subducting at the Sunda and the Andaman trenches. The gap in the blue surface corresponds to the warmest oceanic lithosphere in vicinity of the Wharton Fossil Ridge and the Nintyeast Ridge. The red surface (-1.%) reflects low seismic velocity material beneath the Andaman Sea. Vertically exaggerated topography is shown with a colored isosurface on the top. The brown lines show the active plate boundaries. Blue arrows show relative plate motion and yellow arrows indicate the extension in the Andaman Basin.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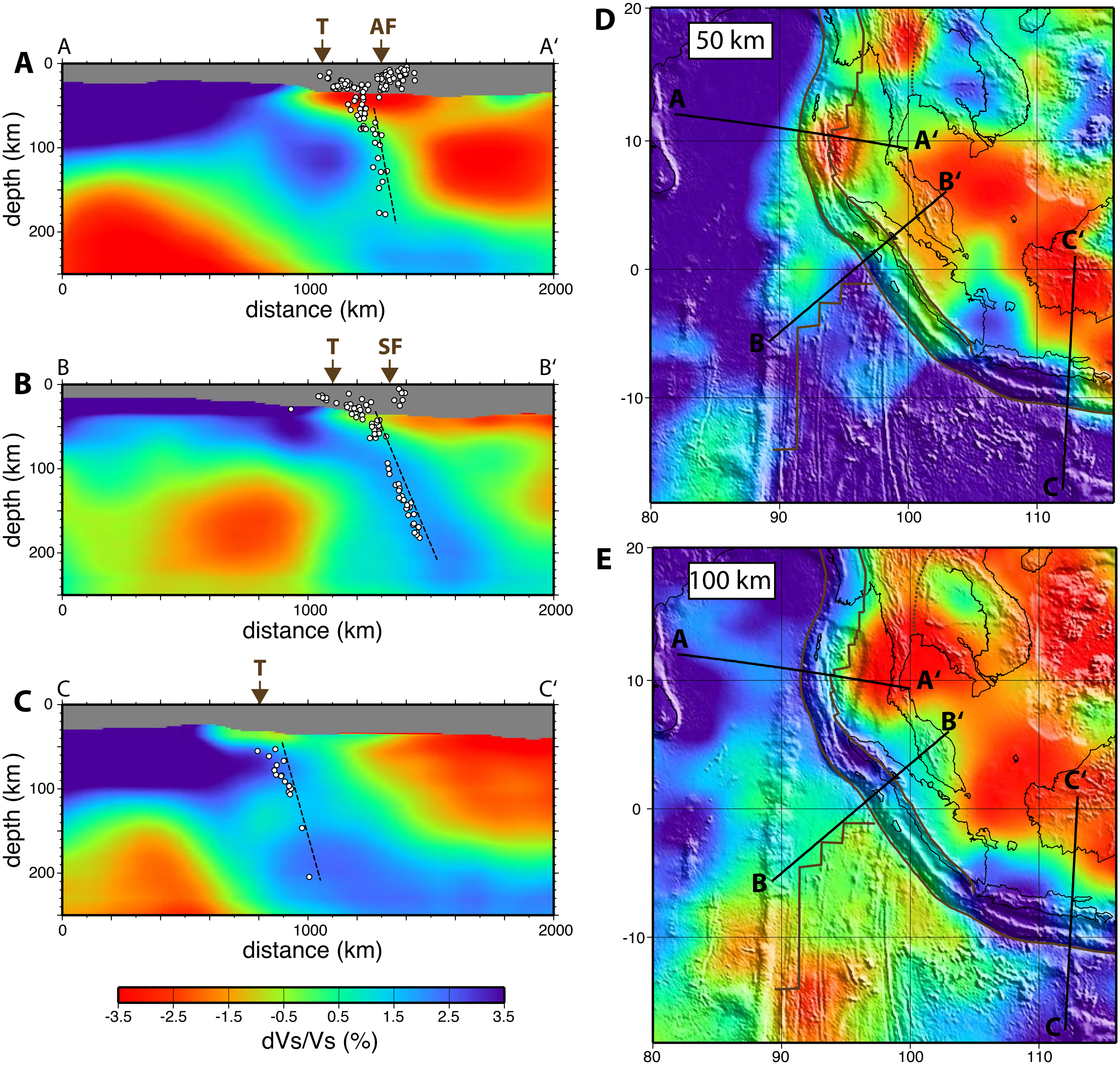

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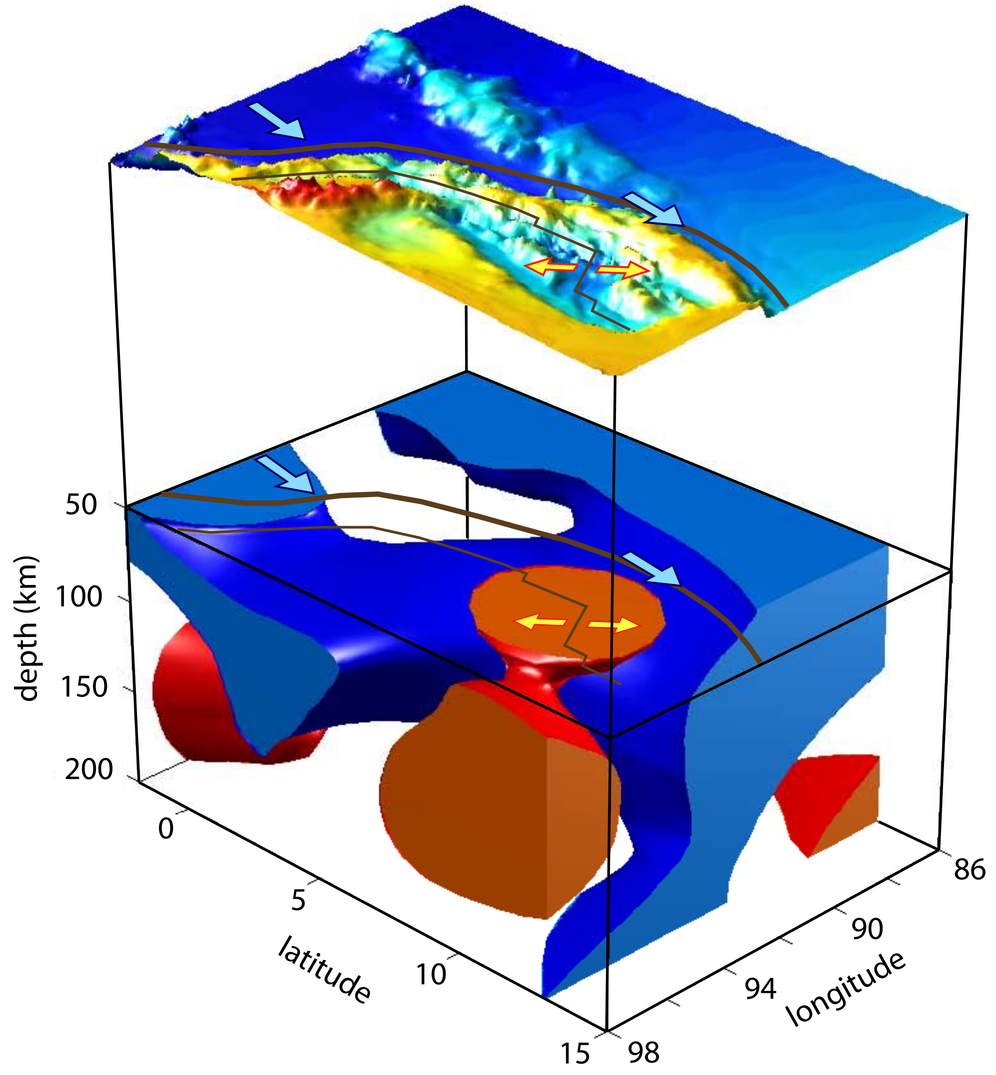

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