Discovery of a massive ancient tectonic slab in the southeastern Indian Ocean: implications for the Indian Ocean geoid low

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A surprising discovery of a massive, ancient, subducted tectonic slab in the southeastern Indian Ocean, known as the southeast Indian slab (SEIS), encompassing the entire mantle down to the earth's core raises a whole set of new questions, and offers opportunities to answer some previously outstanding ones. Evidence for SEIS comes from a high-resolution tomographic study by Simmons *et al.*[1] using arrival times of *P* and *S* waves from distant earthquakes recorded at the seismograph stations of a global network. The slab is apparently derived from an ancient, massive intra-oceanic subduction zone in the Indian Ocean region, which subsequently migrated southwestward. The current position depicts a slab almost 7000 km in length, dipping down from the Kerguelen plateau in the south to the Indonesian arc in the north, reaching the core–mantle boundary at a depth of 2900 km, and flattening against the outer core. Interestingly, the geometry of the slab on the eastern side is almost vertical, forming a complete column between the mantle transition zone and the outer core. It is also interesting that the slab begins to the north of the erstwhile Gondwana supercontinent, which broke up in the early Jurassic (~180 m.y. ago) accompanied by massive volcanic eruptions paving way for the drifting away of most of the constituent continents, including South America, Africa, Madagascar, India and Australia from Antarctica. Previously such slabs were seen beneath Eurasia and North America, but what sets apart the SEIS is not only its massive dimension but the long duration of its persistence in the mantle since ~200–250 m.y. A similar example would be the Farallon plate that sunk beneath North America[2,3], except that it is a younger slab, and unlike SEIS it seems to be present right from the surface downwards. A new implication of SEIS is that such massive subducted slabs can stay intact in the mantle much longer than understood so far.

One of the outstanding issues in the vicinity of the SEIS is the presence of the strongest geoid anomaly on earth, of about –106 m, immediately south of the Indian peninsula. The geoid is an equipotential surface envelope that the earth's oceans would take under the influence of its gravitation and rotation, in the absence of wind and tidal effects, and can be directly derived from the spatial variations of the gravity field. The primary explanation for the undulations seen in the shape of the geoid is related to heterogeneity and dynamics within the mantle. The general understanding is that globally, pieces of slab deep inside the mantle known as slab graveyards associated with Mesozoic subductions, lying above the core-mantle boundary, strongly correlate with geoid lows, whereas zones of active subduction and hotspots correspond to geoid highs[4,5]. Spasojevic *et al.*[6] showed that the slab graveyards are actually high velocity/density dehydrated entities which by themselves cannot produce the geoid lows. However, mantle upwellings caused by dehydration of hydrous minerals in these slabs during their decent, lead to lowering of the mantle velocity/density around them, and could be responsible for the low geoid anomalies. Several studies have attempted to understand the sharpest negative anomaly of the so-called Indian Ocean geoid low (IOGL)[6–9]. Most of the models, however, fail to sufficiently account for the short-wavelength, localized IOGL anomaly south of India. Rao and Kumar[9] examined locally the travel times of the ScS phases which are the seismic shear waves bouncing-off the core-mantle boundary in the Indian Ocean, and confirmed more precisely the presence of high-velocity slab graveyards in the lower mantle which in conjunction with the low-velocity upwellings in the upper mantle, could explain the IOGL. It is, however, clear that there is a need for higher resolution of the tomographic images for better interpretation, and also better tools to resolve the extensive, diffuse, low-velocity regions. Apart from the well-known regions in the upper mantle transition zone and the mantle wedge, there are at least two more dehydration sites in the lower mantle as suggested by Ohtani *et al.*[10], one in the uppermost part of the lower mantle and the other at 1200–1500 km depth, which mark the decomposition of hydrous to superhydrous mineral phases at suitable pressure and temperature conditions.

In the current background of attempting to fit the world's lowest geoid anomaly in the Indian Ocean, it would be interesting to see the implications of SEIS, which can hardly be unrelated to the IOGL given its sheer dimension, proximity and status as a newly found additional slab in the Indian Ocean region. It is also interesting to note that the SEIS slab, as inferred, is exactly adjoining to the demarcated zone of IOGL. This raises the possibility that the IOGL is not a local anomaly but rather an extended one from south of India to southeast of Australia, as a long-wavelength feature whose effect is probably masked in between by the presence of the high-velocity SEIS body, thereby giving an impression of a localized geoid anomaly of the highest value south of India. This also provides for a large additional source for extraction of huge quantities of water in the upper mantle, which along with water extracted from the underlying ancient slabs can generate the required low velocity in the mantle, sufficient to explain the observed very low geoid anomaly. Alternatively, we speculate that the hydrous upwelling derived from the dipping SEIS slab as well as the slab graveyards could get squeezed westward from the mantle wedge, in view of the vertical column of slab blocking on the eastern side. This would lead to a very low velocity/density localized mantle anomaly sufficient to explain the strong geoid low in the IOGL. The above two possibilities, or a combination of both, would form a new set of possible interpretations for the world's lowest geoid anomaly. The real picture, however, would require detailed 3D gravity modelling in the Indian Ocean, from the surface down to the core–mantle boundary, with the assumption of a spherical earth. The modelling would have to incorporate the newly found SEIS structure, scattered graves of slabs on the core–mantle boundary, and massive dehydration from both, which is very likely to produce the

IOGL seen as a local feature south of the Indian peninsula.

The discovery of SEIS demands a fresh look at the current understanding of pre-Gondwana tectonics, plate reconstructions in the Indian Ocean region over millions of years with reference to the slab retreat witnessed in the case of SEIS and constraints on values of sinking rates of slabs in different environments. It also questions the current models of mantle flow in the Indian Ocean region and the associated implications for the anisotropy of seismic velocities usually deciphered from the splitting of components of the shear waves and their derivatives in orthogonal directions. It is well known that mantle flow patterns have a strong link with geometries of slabs, particularly massive ones. The new result also provides ample inputs to modellers who try to develop a holistic understanding of the connection between the Earth's internal structure and the deeper mantle flow patterns (e.g. ref. 11). Various factors would have to be considered in modelling, like the plate driving forces, boundary-zone deformation, mantle pressure–temperature conditions, viscosity, rigidity and stresses, as also the surface topographic variations, structure of the lithosphere, and sinking velocities of subducting as well as detached slabs.

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