Subducting sea floors bridge the mantle divide

A. V. Sankaran

Global seismic data of the passage of earthquake waves through Earth have mainly been responsible for our present knowledge about the structure of Earth. The latter, as we now know, consists of an outer lithosphere made up of rigid crustal plates riding over an inner zone of silicates called mantle, which itself surrounds an innermost zone of metallic core. Further, geochemical, gravitational, magnetic and high-pressure experimental data aided by ever-enlarging computer power, have enabled geoscientists to identify additional subzones within these regions on the basis of properties like pressure, density, temperature, mineralogy and composition.

The mantle, among Earth's interior zones, has a prime role in global volcanism, continental drift, and in the creation as well as destruction of crustal material. Detailed geochemical, isotopic and rare gas abundance studies have revealed that, chemically and mineralogically, the upper and lower sections of the mantle differ and that their thermal currents convected independently[1–3] (Figure 1). The lower mantle is postulated to preserve the primitive or primordial composition as it existed after separation of core, early in Earth's history, whereas the upper mantle is thought to have departed from its original composition, owing to extraction of heat-producing elements like K, U, Th and large ionic radii lithophile elements, during the formation of the crust. Geophysical data also supported this division of the mantle into lower and upper zones, and the junction between them was fixed at 660 km depth, where, seismic wave velocity showed a sudden increase, indicating a discontinuity. The latter discontinuity, also known as the D" layer, is supposed to be caused by mineralogical phase changes to more dense mineral structures or to departure in the major element composition below this point.

While the above mantle structure remained a classic model, considerable geochemical work[4–8] on mantle-derived basalts, during the last thirty years, has brought to light many crucial departures from this ideal model. Particularly significant is their unexpected chemistry differing much from the composition expected of their source within the mantle. The mid-ocean ridge basalts or MORB, derived from the depleted upper mantle, and the ocean island basalts or OIB derived from the undepleted lower mantle (Figure 1) are good examples, in this respect. These findings have, understandably, spurred geophysical and geochemical investigations resulting in the proposal of several models about the nature of the mantle vertically and laterally. Yet, many intriguing questions remained unanswered: (a) the degree of

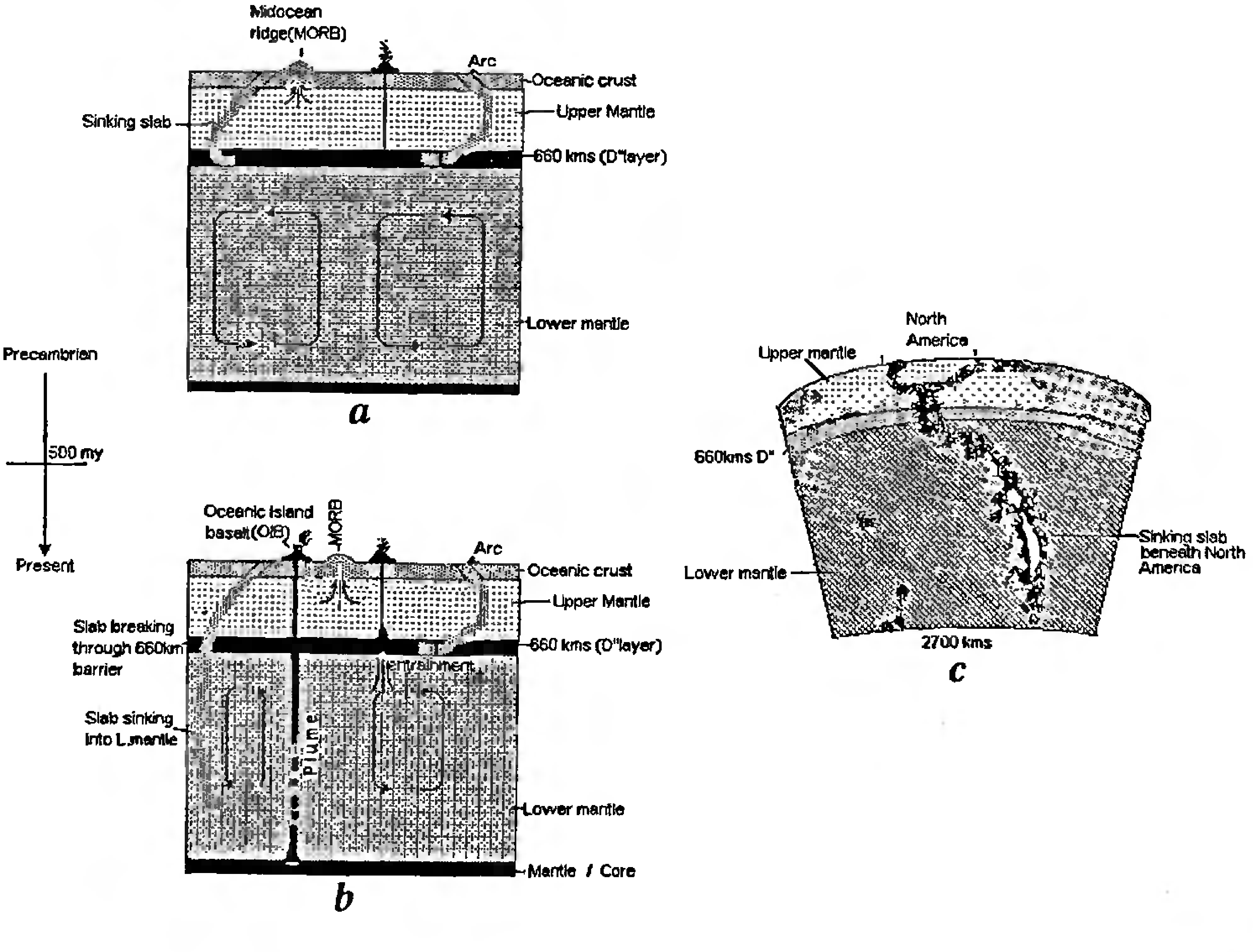

Figure 1. ***a***, Standard geochemical view of upper and lower mantle as two segregated portions during early Earth's history. ***b***, Mantle breaking down in the last 500 million years leading to intermixing of upper and lower mantle (illustration adapted from Allègre[21]). ***c***, Sketch of a tomographic image of vertical slice through the mantle below North America showing the sinking Pacific slab (adapted from Grand *et al.*[20]).

divide between the upper and lower mantle with respect to their physics and chemistry; (b) the extent of the intermixing between these two zones; (c) the reasons for the depletion of primordial chemical constituents that had initially prevailed in the lower mantle, and (d) the fate of the sinking crustal slabs. None of the models proposed, based on the physical and thermal differences or chemical and isotopic anomalies, could bring about any consensus among the scientists, and the various models advanced only served to provide considerable grist for the ongoing debates.

Among the many of the mantle imponderables, the one that has recently brought about some fresh insight and greater agreement among the earth scientists is about the fate of oceanic crusts that subduct into the mantle. These crusts have been forming continuously from the mantle over the past 4.5 billion years of Earth's history, and the older ones among them, after lasting for a few hundred million years or so, have invariably disappeared through subduction. The baffling question about them is whether these subducting slabs stay trapped within the upper mantle or penetrate all the way up to the core. While the geophysicists had pictures of lithospheric slabs sinking up to the core-mantle boundary and were emphatic that their sinking brought about appreciable mixing between the two mantle zones, the geochemists had opposite perception about the fate of the slabs and extent of intermixing. In essence, these developments led to the emergence of two groups – whole mantle convectionists and layered-mantle convectionists. Any attempt to advance compromise models to bring their views closer could, perhaps, be effective, provided unquestionable pictures of the actual happenings to the slabs sinking within the mantle over geologic time, can be obtained.

How these old crustal slabs end up, had indeed remained a fascinating question and an answer to this had a great bearing on our understanding of the geological disposition of Earth's interior and the forces triggering earthquakes and volcanoes. If only X-raying of Earth is possible, the riddle about the fate of the slabs could be solved; but, so far, the seismometer had been the main tool for this purpose, which, unfortunately, lacked the sophistication needed for monitoring the subducting slabs. However, efforts to develop a suitable tool got accelerated during the 1970s and 80s through the adaptation of Computerized Axial Tomography (CAT), a technique originally developed in the field of medicine to scan the brain. The application of this method to probe the inside of our planet was pioneered by Adam Dziewonski of Harvard University and Don Anderson at Caltech[9–12]. In this method, seismologists obtained a three-dimensional picture of the interior of Earth by integrating seismic wave data of thousands of earthquakes recorded simultaneously by stations around the world. These data, obtained on vertical cross-section depthwise, or on spherical shells, enabled the seismologist to prepare a density and temperature distribution profile (displayed on the monitor by appropriate colour discriminants, for example, as blue-coloured colder and red-coloured warmer regions) across the depth zones. The tomographic data could thus generate geometrically related three-dimensional view of zones of varying densities or character of sinking material and also depict the pattern of movements of the convecting currents, thus virtually helping to map the mantle zones.

In 1992, Yoshio Fukao (Nagoya University, Japan) and colleagues[13], through comprehensive tomographic pictures, found subducting crusts pushing 200–400 km deep into the lower mantle, while in few other places they had noticed that similar slabs were deflected sideways. Ulrich Christensen (Max Planck Institute for Geochemistry) and David Yuen (University of Minnesota) also observed similar features in their studies[14]. In an indirect approach to the same problem, mineral physicists in a few centres like Raymond Jeanloz's laboratory at the University of California (Berkeley), Carnegie Institution (Washington) and University of Tokyo (Japan), carried out a series of experiments subjecting upper mantle minerals to pressures and temperatures of lower mantle to assess the resultant mineral phase's crystalline structure, density and other properties. Their aim was to compare the latter data with those derived through seismological observations about the lower mantle. Such comparisons, the experimenters felt, would be able to reveal whether or not mineralogical transformations support intermixing of the two zones over geologic time. Their results showed that no significant mixing took place between the two and that the mantle had a layered pattern and both the upper and lower mantle were composed of different materials, which differed in density by a few per cent[15–18].

In another series of experiments and computer simulation studies to investigate the fluid dynamical interaction across the interface of two separate convecting fluids, Hans-Claude Nataf (Ecole Normale Superiure, Paris) and Peter Olson (Johns Hopkins University, Baltimore), found that pockets of mixture of the two develop, implying thereby that over geologic time, some amount of leakage takes place between upper and lower mantle. Seismic tomography and computer simulations by later workers in Canada, Japan and USA have also revealed complex flow patterns associated with mineral transformations; also, upper mantle material tended to stagnate at the interface and occasionally was even driven down into lower mantle[13,18].

Now, in separate seismic tomographic studies published recently[19,20], that may set at rest the ongoing mantle debate, van der Hilst (a seismologist at MIT, Cambridge, USA), with his colleagues, and Stephen P. Grand (University of Texas, Austin), were able to obtain, unlike the fuzzy tomographic images of earlier years, better pictures. They showed slabs of subducting ocean floors plunging to the bottom of the mantle, suggesting good mixing of upper and lower portions of mantle. In the studies by the MIT group, P-waves or the compressional waves of over 100,000 earthquakes received at seismic stations around the world were processed in computers and millions of data points were evaluated. Their studies revealed slabs of rock, some 500 km wide and thousands of kilometers long, distinctly colder than the surrounding mantle rock, slicing into the mantle at depths of 1300 km or more.

Stephen Grand, at Texas, studied the slower S-waves or the shear waves, which get reflected at boundaries, and found two slabs plunging, one beneath the Americas, from Siberia to South America, and another beneath Europe and Asia, from the Mediterranean to Indonesia. The pictures exhibited sinking slabs beneath the Caribbean and central Japan also. According to Grand, the slabs were seen extending up to the top of the core. But what happened to them thereafter, was surprisingly, revealed when some of the earlier tomographic pictures were reexamined. The latter, though not as sharp as the recent ones, yet indicated the sinking slabs surviving their prolonged journey down the mantle up to some 300 km above the core, a region virtually serving as their ultimate resting place, before getting reborn, after finally uniting back into the mantle from which they evolved millions of years back.

In the views of both Stephen Grand and van der Hilst, the slab sinking beneath Europe and Asia is the floor of the ancient Sea of Tethys that once lay between India and Asia and other lands in the north. The slab beneath the Americas represents a large section of Pacific Ocean floor (called Farallon Plate, which at one time bordered North and South Americas on their western sides) sinking eastwards since mid-Cretaceous time beneath the two continents. Critics have pointed out that the location of this subducting Pacific ocean floor slab, as revealed by these tomographic studies, does not correlate with the high amount of earthquake and volcanic activities usually associated with subduction zones; actually, volcanism and recurring earthquakes are taking place elsewhere, in northwest Pacific region, beneath Japan, eastern Siberia and Aleutian islands and geophysicists have, therefore, identified sinking ocean slabs in this region. Van der Hilst explains that initially, during early geologic times, the slab did sink into the lower mantle, but subsequently, some ~45 million years ago, the slab changed its direction due to some plate rearrangement which led to the 'separation of Japan from continental Asia and initiation of subduction beneath the Philippine sea plate'. During post-Eocene times, it migrated clockwise leading to the deflection and making it difficult for the sinking slab to break through the 660 km transition zone between upper and lower mantle. The authors feel that the pockets of cold rock they came across at 1800 km depth beneath Asia are the remnants of the ancient Pacific floor that had originally subducted into the lower mantle till the plate rearrangement took place. They also believe that the northwest Pacific plate will, ultimately, resume its progress into the lower mantle. According to them, the structural complexity in the transition zone suggests that the 'Earth's present day convective regime is predominated by some form of whole mantle overturn and their intermittent mantle stratification is a local and transient phenomenon only'[19].

In an yet another recent contribution to mantle convection, unifying the views of both geochemists engaged in volcanic studies and geophysicists interpreting tomographic pictures, Claude Allègre[21] (Institute for Physics of the Globe, Paris) says that the disagreement between the two groups is bound to be there since they are interpreting different periods of geologic history. His calculations of isotopic systems – mainly Sr, Nd, Hf and also U-Th-Pb as well as rare gases, have provided him a way to calculate the amount of material exchanged between the mantle zones over geologic time. These have enabled him to infer that the 'convection style evolves through time' (Figure 1 *a*, *b*). The geochemical views are based on evolution of mantle over the past 4.5 billion-year period, whereas seismic tomography represents the picture as it exists today, i.e. last 100 million years or so. Allègre feels that the pattern of convection has changed after the first 4 billion years, during which period, the mantle had two-layered, independent convection, whereby the lower mantle retained its pristine composition of the early Earth. However, 500 million years ago, this independent barrier broke down introducing intermixing of the two regions, 'one at whole mantle scale with slab penetration and another on upper mantle scale with which hot spots are associated'. This hypothesis, he says, is clearly demonstrated also in computer simulations he had carried out on two-layered convection system.

Some geophysicists are yet to accept the conclusions about the subduction history of the oceanic crusts made out from the latest tomography studies, particularly with regard to the estimates about the exact width of the features and the amplitude of these anomalies[22]. Also, they feel that seismically fast features need not always be slabs and that such interpretations have to be substantiated in terms of temperature and chemistry. A. W. Hoffman, (Max Planck Institut für Chemie, Mainz, Germany) in a recent comprehensive review of mantle geochemistry[8], sums up that the current mantle controversy is likely to be resolved when 'seismic imaging of the Earth's interior becomes comparable in resolution to that achieved by geochemical mapping, so that geophysical and geochemical data can be more specifically correlated'. Geophysicists are now confident that future tomographic investigations, aimed to secure more refined pictures having high degree of resolution, may convince the scientists doubting the whole mantle convection. Hopefully, geochemists and geophysicists can then jointly formulate better thermal and chemical evolution of Earth.

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A. V. Sankaran lives at No. 10, P&T Colony, I Cross, II Block, R.T. Nagar, Bangalore 560 032, India.