



Figure 1. Rupture generated by the 1995 Great Hanshin–Awaji (Kobe) earthquake. About 150 m of this rupture with an elevation of ~1 m, which cut through the Hokudan Town is now preserved and an earthquake memorial park is built around this feature. What is shown in the foreground is the fault offset visible on a vertical section.

tion by Hisao Ito and others on drilling of the *Nojima* fault was particularly interesting to understand the nature of work being done as a part of post-earthquake studies. The Geological Survey of Japan drilled a 747-m-deep borehole penetrating the *Nojima* fault. Apart from conventional logging, fault zone at depth was studied for changes of the P and S wave velocities, which were determined by Dipole Shear Zone Images. Permeability structure and width of the fault zone were estimated from the surface trapped wave observations. The demonstration of a soil sample named geoslicer developed by T. Nataka and K. Shimazaki showed a new method to extract undisturbed slices of unconsolidated Quaternary sediments. This is an important development in sampling techniques for active faulting research as it enables

us to carry out high resolution analyses of samples most effectively.

On the field trip, participants examined the effect of recent deformation and evidences of palaeoseismicity. On 23 January an open house was held where some of the victims and those who live in the neighbourhood of the *Nojima* fault shared their experiences of the Kobe earthquake with the seminar participants. Many of the scientists, especially those from California who live near the active faults shared their concerns with Awaji residents not as scientists but as ordinary citizens who too are compelled to deal with earthquakes in their daily life. We could sense the strong bond that was built between the people and the scientists over the meeting that lasted for about two hours. This is an excellent example

of an outreach programme to assure the people of the efforts that are being initiated to understand the problems regarding the seismic hazard. The meeting ended with field trip to Median Tectonic Line (MTL). This structure which cuts across Japan forms an important area of tectonic studies in Japan.

The impression we carried from this meeting is that earthquake science has advanced much further and the Hokudan Symposium has set the stage for major advances in active faulting research. One major development in the recent years has been in the field of imaging the fault structure at depth through tomographic studies. The second significant advance is in the field of predicting ground motions. The third is the rapid growth of earthquake geology and its application in characterizing the active faults. Drilling into a fault that caused a large earthquake provided data useful for future studies as it helped validate many assumptions. There was a general consensus that some of the large earthquakes do not strike anywhere, but only in anomalous areas that can be detected with geophysical and geological methods. Even though we are quite far from earthquake prediction per se, combining seismological studies with geological, geochemical and geophysical investigations would certainly provide us with better understanding of the earthquake process and contribute to the mitigation of earthquake hazards.

C. P. Rajendran and Kusala Rajendran, Centre for Earth Science Studies, Akkulam, Thiruvananthapuram 695 031, India

RESEARCH NEWS

Some recent investigations about dynamics of mantle upwelling

A. V. Sankaran

Ever since earth took shape 4.5 billion years ago, its interior has been cooling essentially through volcanic upwellings and these have progressively led to

changes in its physical and chemical makeup¹. According to the plate tectonic concepts, fresh crust such as the extensively studied mid-ocean ridge

basalts (MORB), developing at the ocean bottoms along divergent plate boundaries are products of thermal upwelling while hotspots²⁻⁵, superplumes

and superswells⁵⁻⁹ are examples of upwelling away from plate (intra-plate) boundaries. Studies by scientists of different disciplines on the internal dynamics of such inter- and intra-plate volcanic upwellings have so far yielded a variety of interpretations. Some of them, in fact, have even linked major magma upwellings (superplume events, flood basalts, etc.) in earth's history to recurring geomagnetic reversals⁶⁻⁸, or to continental break-up¹⁰ or to the periodical transit of earth through clumps of galactic dark-matter¹¹ having immense heat generating potential. Yet, the subject has still remained vaguely understood. The spate of explanations emerging from astrophysical, geophysical, geochemical and isotopic studies have been so confusing that they have activated earth scientists, in the last few years, to have a fresh look through newer investigative approaches into the geodynamics of the mantle. These have yielded new models about thermochemical convection in the mantle, intermixing of mantle layers, magma generation, influence of density, viscosity and other physical parameters on magma transport through the lithosphere to the regions of volcanism.

Among the volcanic upwellings, 'superswells', a type of buoyant mantle melt or mantle 'aneurysm' as it were, of massive size have come in for extensive studies by geophysicists^{9,12,13}. Some of the hot spot upwellings (cylindrical column of mantle magma rising to plate surface) are characterized at its surface end by existence of a shallow sea-floor or a 'swell', extending for a few hundred kilometers, caused by the uplifted mantle. When this uplift extends laterally to several thousand kilometers, the term 'superswell' is applied⁹. The mantle below such superswell areas is hotter than regions of downwelling that take place at convergent plate boundaries, where the sinking cold slabs (subduction) of lithosphere reduces the mantle temperature. This scenario would imply that superswell regions invariably should occur away from the subducting plate edges and such areas being hotter exhibit more volcanism as hot spots and seamounts (isolated undersea volcanic mountain), compared to normal lithospheric regions.

Three superswells around the globe are well recognized (Figure 1). One of

them lies below South Africa uplifting the ancient craton here. The second superswell occurs beneath French Polynesia, in the South Pacific region. The third, the Darwin Rise, lies in the north Pacific and this one is considered, on the basis of plate reconstruction, as the Cretaceous predecessor (palaeo-superswell) of present French Polynesian superswell⁹. Within the perimeter of the latter, are the hot spot volcanic island chains like Society, Cook, Austral, Tuamotu, Marquesas and Easter. Seismic tomography and other geophysical studies have shown that upwelling in the south Pacific region arises from the mantle either in its upper zone or in the transition zone around 670 kilometer depth⁹. Likewise, the anomalous elevation of the African craton to more than 1 kilometer above the sea-level is explained, on the basis of global seismic tomographic studies¹⁴⁻²⁰ as largely due to the presence of superswell beneath its eastern and southern portions. Actually, this superswell is described as the continental equivalent of the Polynesian superswell²¹ beneath south Pacific Ocean floor. Studies on this superswell indicate magma initiation at the core-mantle boundary (CMB) through active small-scale convection or due to the 'instability of a thermal boundary layer at the base of the mantle'. It is now inferred that the buoyant mantle melt rising from this depth at a rate of few centimeters per year has been a significant force pushing up the African lithosphere along with the sea floor around and extruding hotspot volcanism at a number of places (17 sites)^{19,21}.

Three possible modes of mantle dynamics have been advanced^{6,9,19,22,23} to explain the topographic elevation associated with superswell: (a) pure lithospheric thinning through the stretching of plate; (b) chemical buoyancy through spreading of a layer of mantle depleted by plumes; (c) dynamic support through upwelling in convecting mantle. However, observations on the basis of heat flow, gravimetric, bathymetric and seismic studies strongly favour the last one for the occurrence of uplifted seafloor and excess volcanism in such regions.

In a recent laboratory study²⁴ to understand the mechanisms behind hot spot and superswell upwellings, Anne Davaille (Laboratoire de Dynamique des Systèmes Géologiques, Paris) observed different patterns of thermal convection developing in her experiments. In a large tank she filled two layers of viscous fluids (varying mixture of water, salt and cellulose to obtain initial density and viscosity differences), one on top of the other, which at the beginning were kept isothermal, but suddenly cooled from above and heated from below. The heat and mass transfer across the interface of the fluid layers i.e. thermochemical modes of convection were monitored during systematic variation of composition, density and viscosity of the fluids. It was found that the buoyancy forces generated within the fluid layers dictated the patterns of convection that developed. Thus when the ratio of density differences between the layers to the density generated by thermal expansion of fluids when heated exceeded 1, the buoyancy effects had

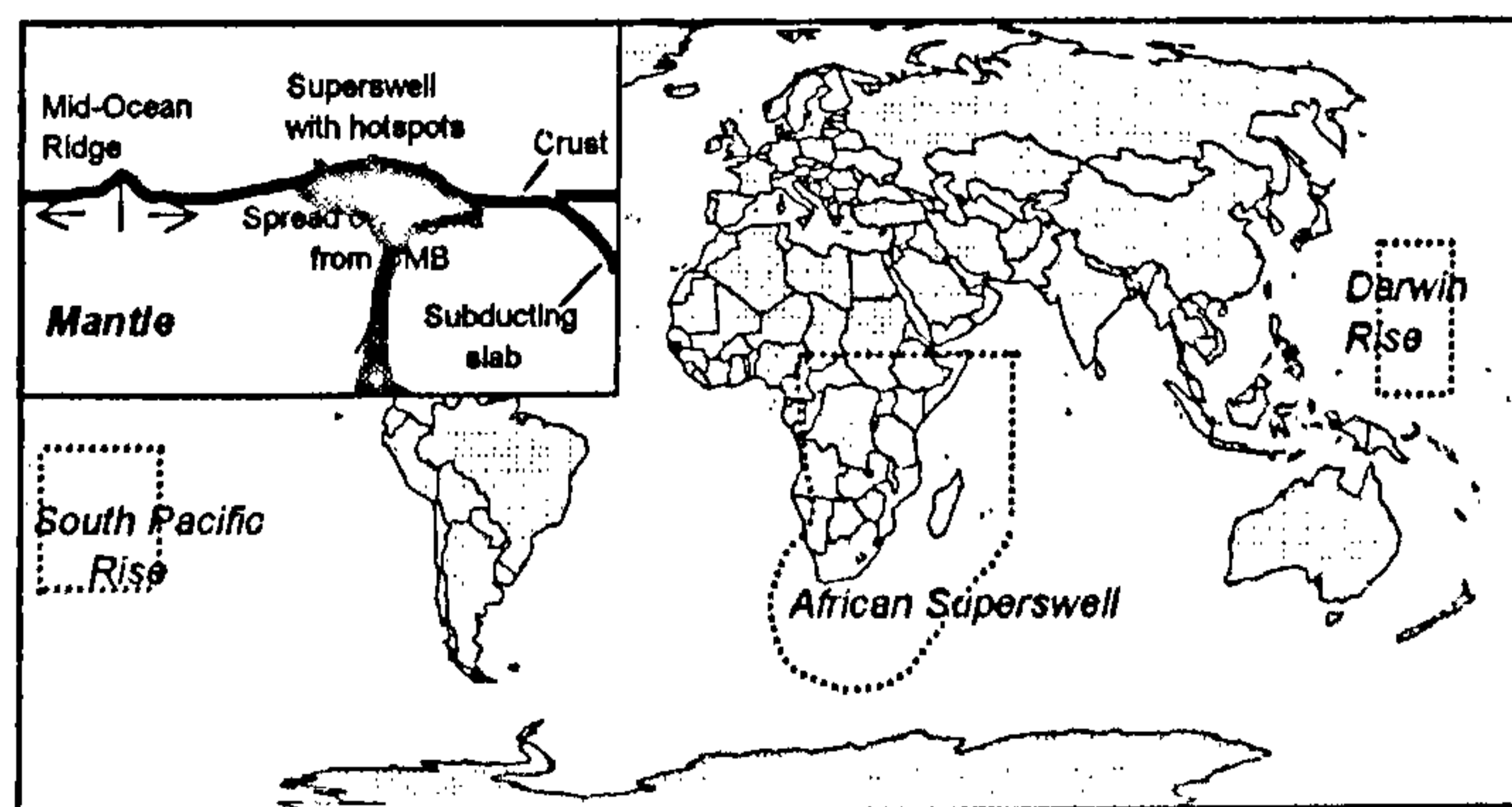


Figure 1. Locations of major superswells (oceanic and continental). Inset shows cross section of superswell beneath a plate.

little impact on the chemical layering except to give off plumes from the density interfaces; but, when the ratio fell below 1 (0.3 or 0.5), the interface deformed and gently domed up. In effect, it was found that even small chemical heterogeneity altered the convection modes. Thus, in her experiments, two types of convection regimes developed – a strongly 'stratified regime', which tended to 'heat and stabilize features compared to classical thermal convection', and a 'doming regime', which occurred when the density at the base of lower layer, heated from below, was smaller compared to the cooled upper layer. Depending upon the stabilizing or the homogenizing tendencies across the two layers, the interface between them deformed or domed and slowly ascended to the top only to get cooled and become chemically denser and sink back to the bottom. This up and down motion or oscillation was repetitive and she found that five such cyclic oscillations produced sufficient intermixing of the fluid layers. Hot cylindrical plume extrusions were also observed to rise from the top surfaces in both types of regimes and this further tended to eliminate heterogeneities in the fluids and eventually led to homogeneity.

Based on the laboratory experiments, Anne Davaille modeled that the mid-mantle interface will lead to doming, 1000–6000 km in lateral extent, oscillating up and down on a time scale of 100 Myr to 1 Gyr with several magma plumes rising from their top surface. According to her, the two present day superswells may represent two different stages of the same process. The African superswell may be in the early stage of dome formation and ascent while the Polynesian superswell would correspond to a more advanced state, which had already gone through the whole cycle. She has concluded that the classic single style of mantle dynamics through time should be abandoned as the mantle is likely to have evolved from strictly stratified convection early in earth's history, more than 4 b.y. ago, to doming and hot spot regimes today. Applying scaling laws for the mixing rate, she has found that the quasi-periodical oscillation of superswell should have homogenized the mantle layering and spread within 0.3 Gyr (for this CMB

layer) to 4 Gyr (for stratification at mid-mantle). Such a model of mantle dynamics and evolution can also account for many of the unanswered geochemical anomalies posed by layered mantle concepts. The experiments of Anne Davaille put present day earth as weakly stratified, a view that parallels similar conclusions arrived earlier through geochemical and seismic tomographic investigations^{1,20,25}.

While above upwellings of intraplate doming and hot spot volcanism dwell on thermochemical convection modes, a series of geophysical experiments recently completed in the south Pacific Ocean have discussed at length another aspect of mantle dynamics operating beneath divergent plate boundaries, sites where mid-ocean ridge basalts (MORB) evolve. The topography of these mid-ocean ridges, the manner of their lateral spread as new oceanic lithosphere is created, the tectonic features associated with such magma upwelling all came to be better understood as a result of extensive undersea mapping undertaken during the 1970s. These pioneering oceanographic studies were carried out along two classic spreading centres, viz. Mid Atlantic Ridge, stretching between the South American and African plates, right in the middle of the Atlantic Ocean and along the East Pacific Rise (EPR), running roughly N–S on the eastern part of the Pacific Ocean, between the Pacific and Nazca Plates. The studies here have revealed some asymmetry in the behaviour of the plates lying on either side of the EPR ridge axis. For example, plate movement on the EPR, which is a broader plate, is faster (about 145 km/million years) than on the Nazca plate (45 km/m.y). Also, the sea floor beneath the EPR side subsides more slowly and exhibits greater volcanic activity than on the Nazca Plate to its east. Explanations for this asymmetry and presence of a wide shallow seafloor in this region formed the subjects for the series of recent geophysical investigations.

The formation of new oceanic crust at the spreading plate boundaries requires immense volume of magma to ascend from the mantle. It is estimated that roughly three cubic kilometers of oceanic crustal rock are added to earth's surface each year along the mid-ocean ridges around the globe. Though the

classic view visualizes that the asthenosphere, lying below the lithosphere, rises to fill the gap produced by the spreading plates, the exact source of the melt, its extent, both laterally and in depth, and its transport to the ridge zone have baffled earth scientists all along. Views have been varying about the melting depth which is considered to be within 60 km or deeper at the garnet stability zone or at around 200 km in presence of water²⁶ as well as about magma temperature, buoyancy, presence of volatiles and its transport either towards a narrow (1–2 km) or a broad zone (several hundred kilometers extent) at the ridge. A series of collaborative experiments^{26–29} involving seismic and electromagnetic observations (Mantle Electromagnetic and Tomography or MELT) were initiated in November 1995 and completed recently in 1999 (ref. 26) with the aim to resolve many of these uncertainties about the upwelling dynamics. The investigators selected for these studies a straight portion of mid-ocean ridge at 15°–18°S on the EPR (Figure 2) where the plates were separating fastest and where they had detected existence of a magma chamber about 2 km below the Pacific sea floor. They had placed arrays of 15 ocean bottom seismometers, electrometers and magnetometers along two parallel stretches 800 km long cutting across the axis of EPR, to record earthquake waves and coupled variations in the electric and magnetic fields. The seismometers were in place for six months and the other instruments, numbering 47, for longer period of 12 months.

The MELT studies evaluating seismic wave velocity^{28–33}, which is influenced by melt volume and interconnected melt inclusions, have indicated that melt generation takes place at depths of 100–130 km and, as per electromagnetic data, even further down at 170 km depth. Further, the transport of this melt is thought to extend over a wide region of the mantle and not confined to any narrow column just beneath the ridge axis. Their data have also revealed unequal extension of melt (Figure 3), which happens to be 300–400 km to the west of the ridge but only up to 150 km to its east^{26,34}. The investigators ascribe this feature as the cause for the observed asymmetry in volcanic activity, subsi-

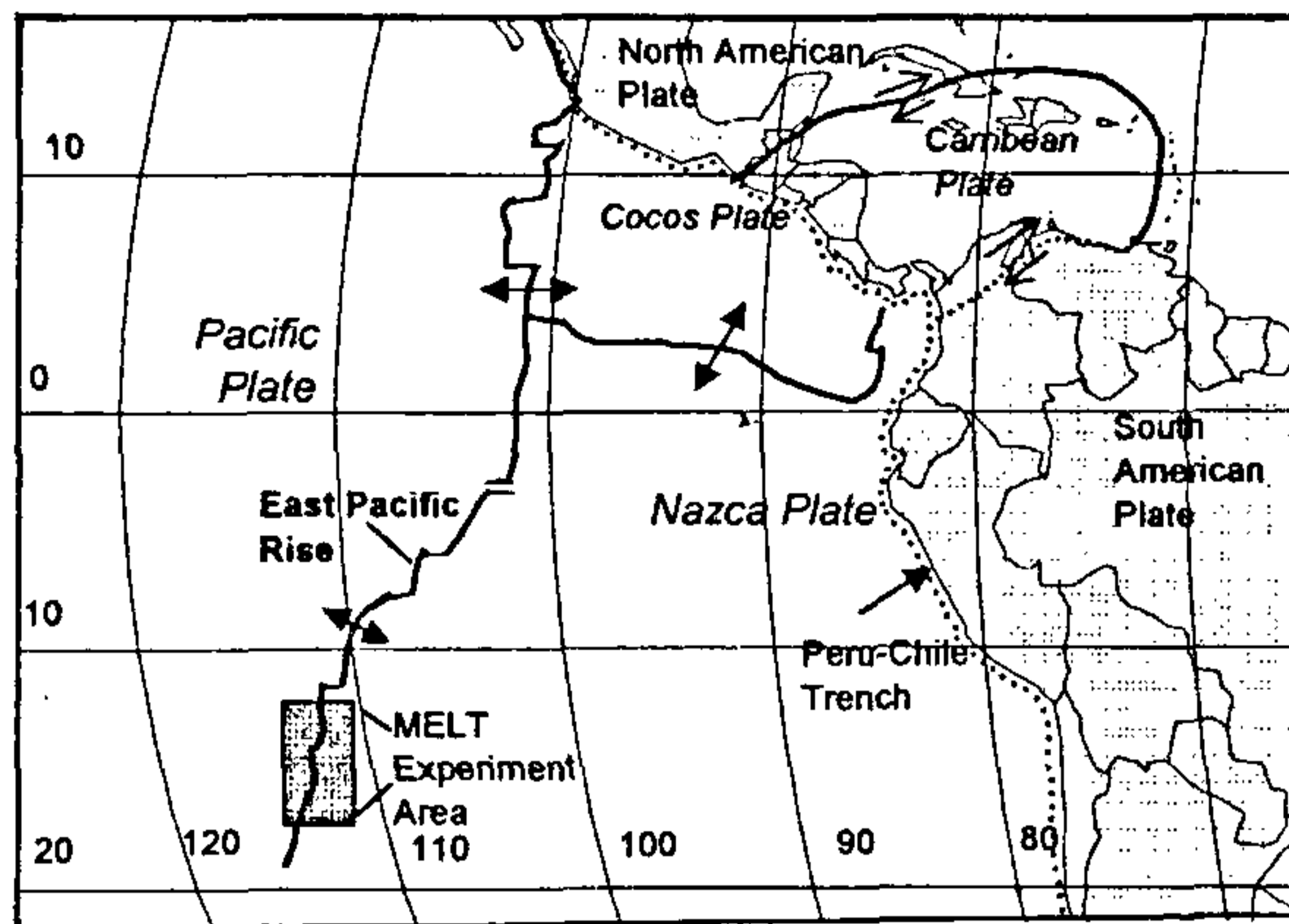


Figure 2. Map showing location of MELT study area between 15 and 18°S latitude. Arrows at plate boundaries indicate the direction of movement of the plates. Dotted line along the coast of South America represents the subducting Nazca plate beneath the South American Plate.

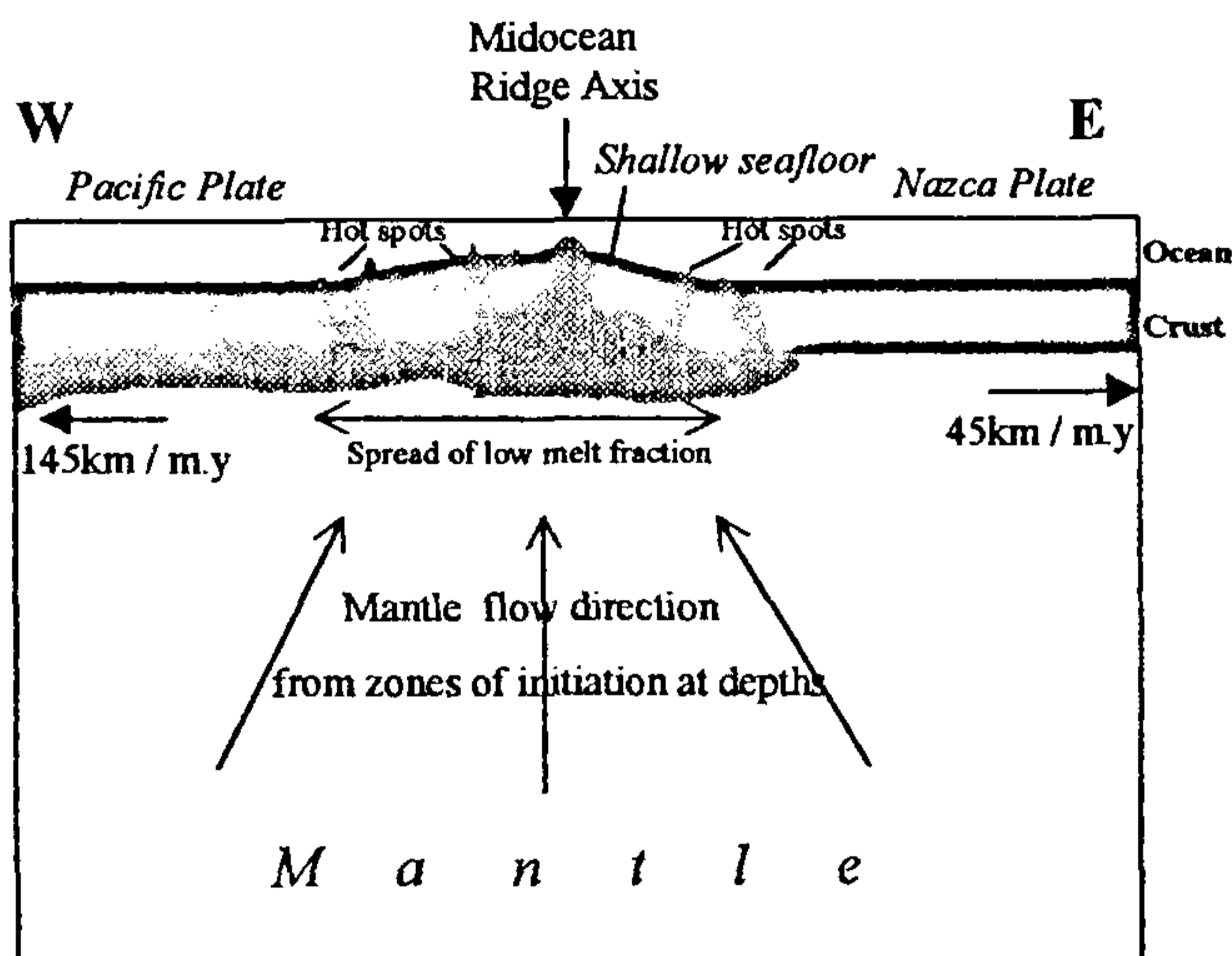


Figure 3. Illustration of MELT model of the mantle beneath East Pacific Rise. The asymmetric spread of the melt fraction can be seen to extend more to the west of the ridge than to its east. Note the floor of the ocean is uplifted to form a shallow region.

and spreading rates and also the al thickness and density variations v the ridge^{27,34}. The electromag- studies²⁶ involving measurement of ical resistivity structure of the le below the ridge have also ght out an asymmetric resistivity re – a lower resistivity to the west eating a broad spread of low melt on extending down to 150 km, r resistivity to the east indicating a

mantle of depleted melt and volatiles. Further, the studies showed a sharp transition at the ridge axis between the low melt region on the west to the dry region on the east, quite unlike the gradual transition over a distance of more than 100 km to the east, observed through seismic studies. The dissimilar resistivity data, however, are in consonance with asymmetry observed here.

The comprehensive MELT experi- ments do not support earlier view³⁵ of narrow focussing of upwelling magma along ridge axis. Upwelling here is considered mostly 'passive' or driven by plate motion and buoyancy controlled mobility of flow is thought to be very small which may even be hindered by the viscosity of shallow mantle. Un- doubtedly, understanding of the various factors operating behind magma upwel- ling right from its generation deep down the mantle to its transport to divergent or convergent plate boundary surfaces, has benefited from these studies. How- ever, some earth scientists have ex- pressed that they would like to await results from further studies presently being carried out by a few groups, be- fore applying the recent models derived from laboratory experiments²⁴ or field observations from a narrow zone²⁸⁻³⁴, to the other regions of earth. Geologists depend heavily on seismic wave propa- gation characteristics to detect mantle heterogeneities, phase changes and density differences within earth's inter- ior zones and hence their hesitation to accept immediately some of the new findings appear justifiable inasmuch as seismic waves lack adequate sensitivity to discern small mantle heterogeneities, non-horizontal mantle interfaces and are affected by anisotropy arising from preferred orientation of minerals³⁶. However, one aspect on which there appears better consensus among them is about the urgent need to review con- cepts on earth's internal dynamics and resultant external manifestations with the changing physics and chemistry of its interior over the last 4.5 billion years. That recent contributions to man- tle dynamics have prompted revision of earlier views about high topography of lands appears evident in the current speculations linking some of the up- lifted terrains in western United States and northwest Himalayas to behaviour of mantle beneath them^{37,38}.

1. Allègre, C. J., *Earth Planet. Sci. Lett.*, 1997, **150**, 1-6.
2. Wilson, J. T., *Can. J. Phys.*, 1963, **41**, 863-870.
3. Morgan, W. J., *Nature*, 1971, **230**, 43-44.
4. Morgan, W. J., *Mem. Geol. Soc. Am.*, 1973, **132**, 7-10.
5. Sankaran, A. V., *Curr. Sci.*, 1998, **75**, 85-89.

6. Larson, R. L., *Geology*, 1991, 19, 547-552.
7. Larson, R. L., *Sci. Am.*, 1995, 272, 66-71.
8. Larson, R. L. and Olson, P., 1991, 107, 437-444.
9. McNutt, M. K., *Rev. Geophys.*, 1998, 36, 211-244.
10. Courtillot, V., Jaupart, C., Manighetti, I., Tapponnier, P. and Besse, J., *Earth Planet. Sci. Lett.*, 1999, 166, 177-195.
11. Abbas, S. and Abbas, A., *Astroparticle Phys.*, 1998, 8, 317-320.
12. Nyblade, A. A. and Robinson, S. W., *Geophys. Res. Lett.*, 1994, 21, 765-788.
13. McNutt, M. K. and Judge, A. V., *Science*, 1990, 248, 969-975.
14. Su, W. J., Woodward, R. L. and Dziewonski, A. M., *Nature*, 1992, 360, 149-152.
15. Williams, Q. and Garnero, E. J., *Science*, 1996, 273, 1528-1530.
16. Wen, and Hemberger, D. V., *Science*, 1998, 279, 1701-1703.
17. Bunge, H. P., Richards, M. A., Bertelloni, C. L., Baumgardner, J. R., Grand, S. P. and Romanowicz, B. A., *Science*, 1998, 280, 91-95.
18. Bonatti, E., Seyler, M. and Sushevskaya, N., *Science*, 1993, 261, 315-320.
19. Lithgow-Bertelloni, C. and Silver, P. G., *Nature*, 1998, 395, 269-272.
20. Van der Hilst, R. D., Widiyantoro, S. and Engdahl, E. R., *Nature*, 1997, 386, 578-584.
21. Nyblade, A. A. and Robinson, S. W., *Geophys. Res. Lett.*, 1994, 21, 765-768.
22. Sandwell, D. T., Winterer, E. L., Mamerickx, J., Duncan, R. A., Lynch, M. A., Levitt, D. A. and Johnson, C. L., *J. Geophys. Res.*, 1995, 100, 15087-15099.
23. Phipps Morgan, J., Morgan, W. J. and Price, E., *J. Geophys. Res.*, 1995, 100, 8045-8062.
24. Anne Davaille, *Nature*, 1999, 402, 756-760.
25. Sankaran, A. V., *Curr. Sci.*, 1997, 73, 901-903.
26. Evans, R. L., Tartis, P., Chave, A. D., White, A., Heinson, G., Filloux, J. H., Toh, H., Seama, N., Utada, H., Booker, J. R. and Unsworth, M. J., *Science*, 1999, 286, 752-756.
27. The MELT Seismic Team, *Science*, 1998, 280, 1215-1218.
28. Canales, J. P., Detrick, R. S., Bazin, S., Harding, A. J. and Orcutt, J. A., *Science*, 1998, 280, 1218-1221.
29. Forsyth, D. W., Webb, S. C., Dorman, L. M. and Shen, Y., *Science*, 1998, 280, 1235-1238.
30. Toomey, D. R., Wilcock, W. S. D., Solomon, S. C., Hammond, W. C. and Orcutt, J. A., *Science*, 1998, 280, 1224-1227.
31. Webb, S. C. and Forsyth, D. W., *Science*, 1998, 280, 1227-1229.
32. Wolfe, C. J. and Solomon, S. C., *Science*, 1998, 280, 1230-1232.
33. Shen Y., Sheehan, A. F., Dueker, K. G., Catherine de Groot-Hedlin and Gilbert, H., *Science*, 1998, 280, 1232-1235.
34. Scheirer, D. S., Forsyth, D. W., Cormier, M. H. and Macdonald, K. C., *Science*, 1998, 280, 1221-1224.
35. Scott, D. R. and Stevenson, D. J., *J. Geophys. Res.*, 1989, 94, 2973-2976.
36. Zhang, S., Karato, S., Fitzgerald, J., Faul, U. H. and Zhou, Y., *Tectonophysics*, 2000, 316, 133-152.
37. Lee, D. K. and Grand, S., *J. Geophys. Res.*, 1996, 101, 22233-22244.
38. Murphy, J. B., Oppliger, G. L., Brimhall (Jr.), G. H. and Hynes, A., *Am. Scientist*, 1999, 87, 146-153.

A. V. Sankaran lives at 10, P and T Colony, I Cross, II Block, R.T. Nagar, Bangalore 560 032, India.

From the archives



Vol. II NOVEMBER 1932 [NO. 5]

The Fiftyfive-Year Rule

The fundamental rules relating to the age of retirement of public servants are obviously empirical and operate unevenly within the limits of even a single branch of service. In the case of the higher posts in the judicial department and cabinet, the fiftyfive-year rule is relaxed, while it is more or less rigidly applied to the appointments in other branches of the administration.

The age limit imposes practically no bar to the assumption of elective offices by retired government servants, and posts in the gift of the Crown are equally exempt from age restrictions. In all business concerns and industrial organizations, the directing authorities hold their offices virtually for life.

It is commonly argued that the age rule, though a purely arbitrary one, must be upheld in order to maintain in the services a uniformly high standard of efficiency which, it is feared, advancing age is apt to sterilize; and to secure for administrative problems that freshness and optimism of outlook which a comparatively youthful and more energetic mind may reasonably be supposed to possess. From an economic stand-point, the age rule scarcely appears to be a sound business proposition, and the consideration that the wastage due to retirement provides some measure of

relief to unemployment seems to be its chief recommendation. Generally speaking, it is true that the efficiency of a person depends not only on his protein metabolism but to a large extent also on the climatic conditions of the country in which he lives; and the influence of adverse environmental factors is likely to be more acute in the case of those who, born in more favourable situations, suddenly find themselves in different and more exacting circumstances, than in the case of races who through centuries have become perfectly inured to them. But this is not all. Of still more fundamental importance is the fact that the treatment accorded to the public servant has a direct influence on his official efficiency. It must be within the experience of all officials that if their career is not embittered by disappointments, and on the other hand, their hopes and ambitions are systematically and periodically fulfilled, their capacity