GLOBAL MAPPING OF THE UPPERMANTLE BY SURFACE WAVE TOMOGRAPHY

Don L. Anderson

Seismological Laboratory, California Institute of Technology, Pasadena, California 91125

Abstract. Surface wave tomography compliments detailed body wave studies by providing a global framework for the lateral variability of the uppermantle. In particular the method allows one to map the mantle beneath the lithosphere and to discuss the fate of overridden oceanic plates. Midocean ridges appear to extend to at least 400 km. By contrast, the very high velocities associated with shields are primarily much shallower. The Red Sea-Afar region is a pronounced and deep low-velocity anomaly. A significant uppermantle anomaly has been found in the central Pacific. This "Polynesian Anomaly" is surrounded by hotspots; Hawaii, Tahiti, Samoa and the Caroline Islands. This may be the site of the extensive Cretaceous volanism which generated the plateaus and seamounts in the western Pacific. Anisotropy indicates deep upwellings, >300 km depth, under midocean ridges, the Afar and the Polynesian Anomaly and downwelling under the western Pacific and the northeastern Indian Ocean. The large fast anomaly under the south Atlantic may represent overridden Pacific plate.

Introduction

Surface waves have long been used to map the structure of the uppermantle. Techniques have recently been developed to simultaneously invert data over many great cicle paths to obtain global maps of lateral heterogeneity (Nakanishi and Anderson, 1982, 1983a, b, 1984, Woodhouse and Dziewonski, 1984), (Fig. 1) azimuthal anisotropy (Tanimoto and Anderson, 1983, 1984, 1985) and polarization anisotropy (Nataf et al, 1984, 1986). Although the results are currently of relatively low resolving power they can be used to discuss the regional structure of the uppermantle on a scale which is comparable to the sizes of the plates and the characteristic lengths which are thought to be important in plate tectonics. In future studies the use of short-period surface waves and higher modes will make it possible to map variations in the thickness and velocity of the seismic lithosphere. In this paper we discuss the presently available results with emphasis on features that relate to the present and past history of the lithosphere. Much of the discussion is contained in the figure captions.

Upper Mantle Models

Nataf et al (1984, 1986) inverted the data sets of Nakanishi and Anderson to obtain the lateral structure and polarization anisotropy of the mantle to depths of 670 km. The resolution of the data is best between about 200 and 400 km. Surface waves, of course, are most sensitive to the shear velocity. Rayleigh waves are P-SV type motion and Love waves are SH type motions. The combined use of Rayleigh and Love waves makes it possible to map variations in the SH/SV ratio, or polarization anisotropy. In regions of the mantle dominated by predominently horizonal a-axis orientation of olivine, or horizontal laminations, we expect SH > SV. This is likely to be the situation where the mantle is flowing horizontally. In regions with abundant dikes, or with a-axis vertical olivine orientations, we expect SH < SV. This is the likely situation in regions of upwelling, magmatic activity or in subduction zones.

In the following we discuss the surface wave inversion results for various depth intervals and present maps of SV velocity and anisotropy. Resolution has been discussed by Tanimoto (1985) and Tanimoto and Anderson (1985).

Parameterization

The mantle is assumed to have the same average properties, including anisotropy, as PREM (Dziewonski and Anderson, 1981). Perturbations are assumed to be smooth between the discontinuities in PREM (60, 220, 400 and 670 km) and to be loosely coupled across these discontinuities (Nataf et al, 1986). Thus, the radial variation in perturbation can change rapidly at physical discontinuities. Woodhouse and Dziewonski (1984) invoked a smooth radial perturbation throughout the upper mantle. The dataset is not yet complete enough to favor one parameterization over another. In the Nataf et al parameterization the variation across the discontinuities is continuous unless the data requires otherwise. In general the perturbations across discontinuities is highly correlated. In both Nataf et al (1984, 1986) and Woodhouse and Dziewonski (1984) the character of the perturbations changes at 220 and 400 km.

At shallow depths we have little resolution because global maps for short-period surface waves have not yet been prepared. Nevertheless, surface waves sense the shallow structure and some information is available.

At a depth of 50 km the major tectonic features correlate well with the shear velocity. Shields and old oceans are fast. Young oceanic regions and tectonic regions are slow. The slowest regions are generally centered near the midocean ridges, some back-arc basins and the Red Sea. The hotspot province in the south Pacific is slow at shallow depths but the shallow mantle in the northcentral Pacific, including Hawaii, is fast. The shields are particularly fast. Anderson and Regan (1983) and Regan and Anderson (1984) give velocity and anisotropy models for the Pacific lithosphere.

At 150 km the slowest anomalies are still centered on the midocean ridges and prominent slow anomalies also occur near the Red Sea, New Zealand and the Philippine Sea Plate. The central Pacific and the northeastern Indian Ocean are fast. Most of the shield

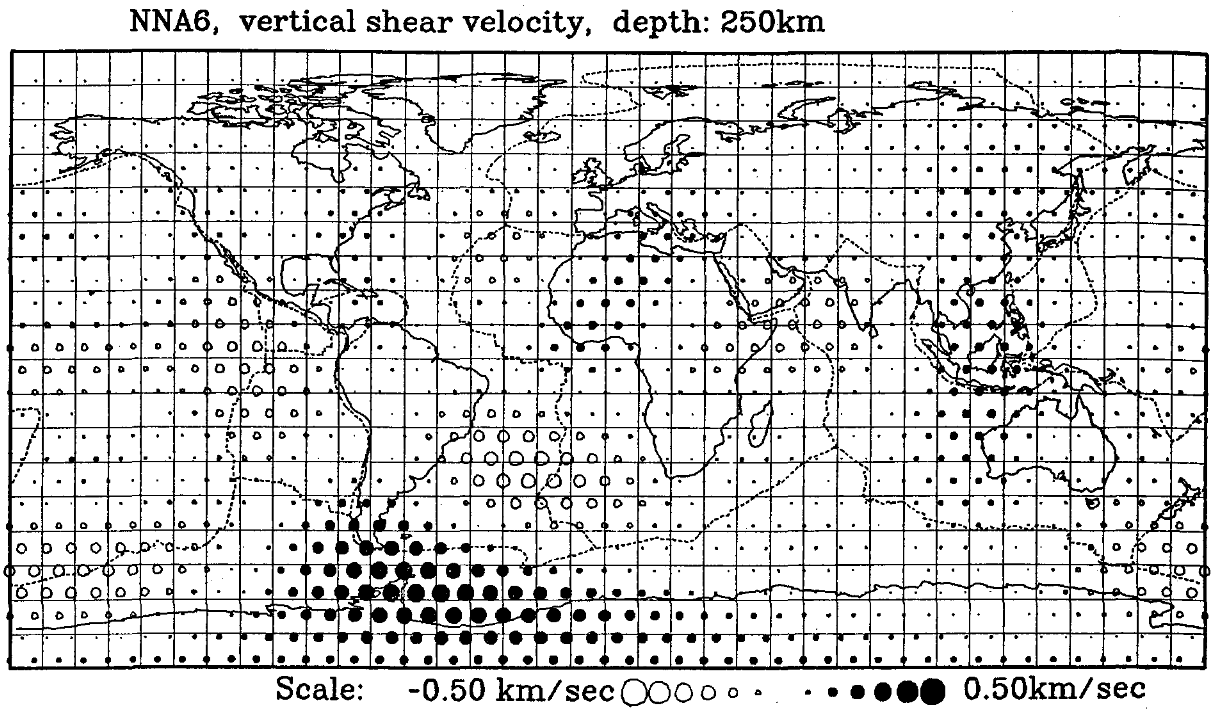

Fig. 1. Map of SV velocity at 250 km depth from sixth order spherical harmonic representation of Nataf et al (1984). Note the slow regions associated with the midocean ridges. The fastest regions are in the south Atlantic, some subduction areas and northwest Africa.

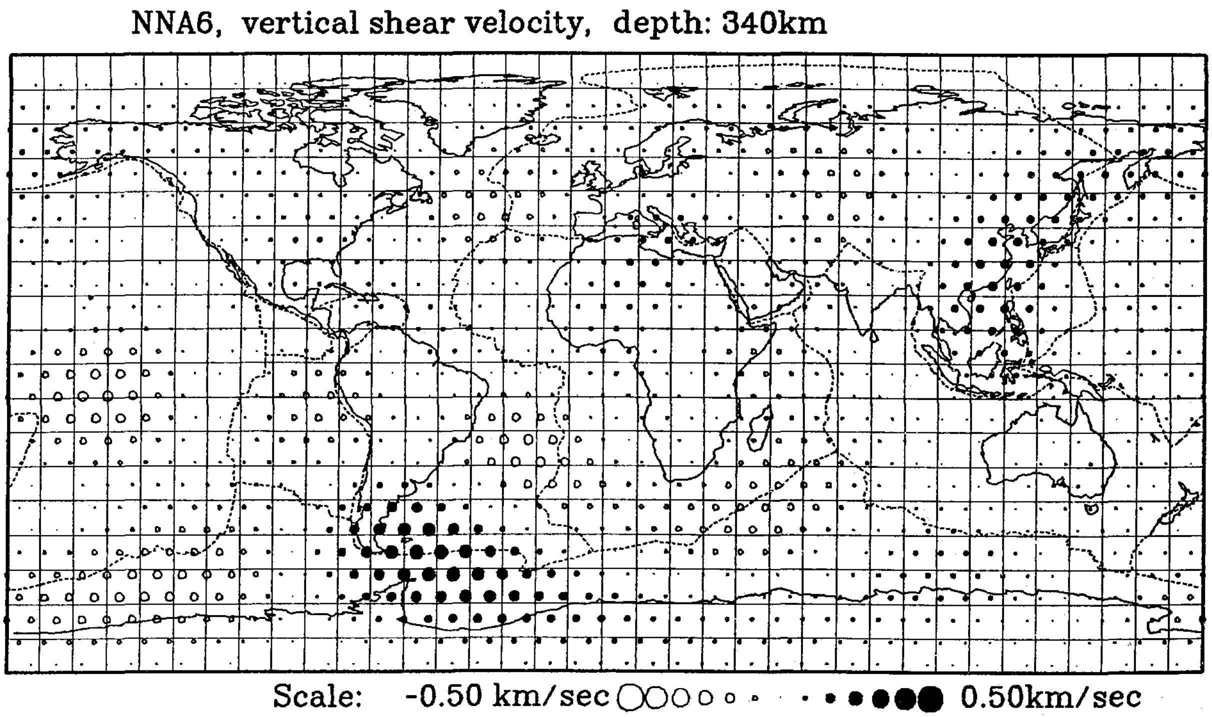

Fig. 2. SV velocity at 340 km depth. A prominent low-velocity anomaly shows up in the central Pacific (the Polynesian Anomaly). The fast anomalies under eastern Asia, northern Africa and the south Atlantic may represent mantle that has been cooled by subduction.

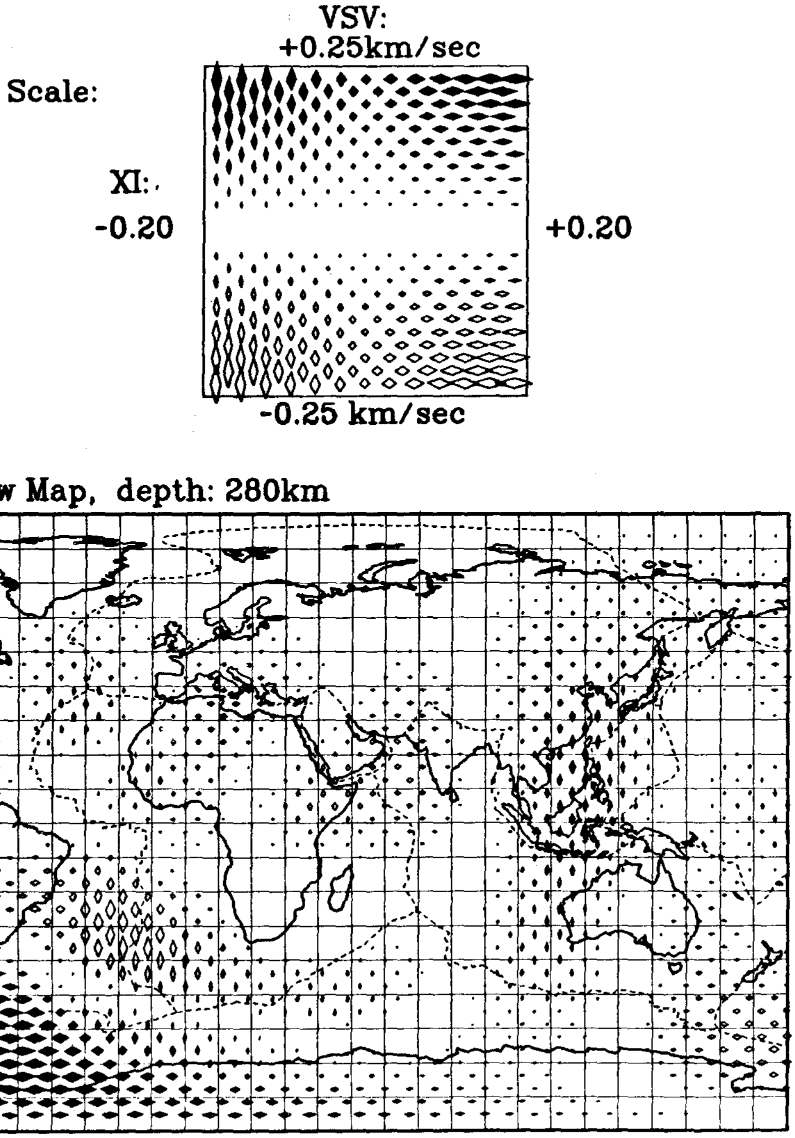

Fig. 3. Seismic Flow Map at 280 km depth. This combines information about shear velocity and polarization anisotropy. Open symbols are slow, solid symbols are fast. Vertical diamonds are SV > SH, presumably due to vertical flow. Horizonal diamonds are SH > SV. Slow velocities are at least partially due to high temperatures and, possibly, partial melting. Regions of fast velocity are probably high density as well. The south central Atlantic and the East Pacific Rise appear to be upwelling buoyant regions. Similar features occur in the central Pacific and the Afar. The western Pacific and northeastern Indian Ocean appear to be regions of downwelling.

areas are still very fast at this depth. The Arctic Ocean between Canada and Siberia is slow.

At 250 km (Fig. 1) there is some similarity with the shallow depths but the close correspondence with surface features is starting to disappear. The midocean ridges and the Red Sea are still evident as slow anomalies but island arcs are mostly fast. This may be related to the subduction of cold lithosphere. Asia and eastern North America are broad high-velocity regions. A new prominent low-velocity region appears in the central Pacific. This region is roughly bounded by Hawaii, Tahiti, Samoa and the Caroline Islands. We refer to this as the Polynesian Anomaly. This feature may be related to the extensive volcanism which occurred in the western Pacific in the Cretaceous when the Pacific plate was over this anomaly. The northern and southern Atlantic are also slow. Northern Europe and Antarctica are mainly fast.

The anisotropy parameter, XI, is negative in a band extending from the Arctic Ocean down western North America, the East Pacific Rise and then sweeping NW across the southern and western Pacific, across the Polynesian anomaly, to the island arcs from Kamchatka to Sumatra. XI is also negative along the midatlantic

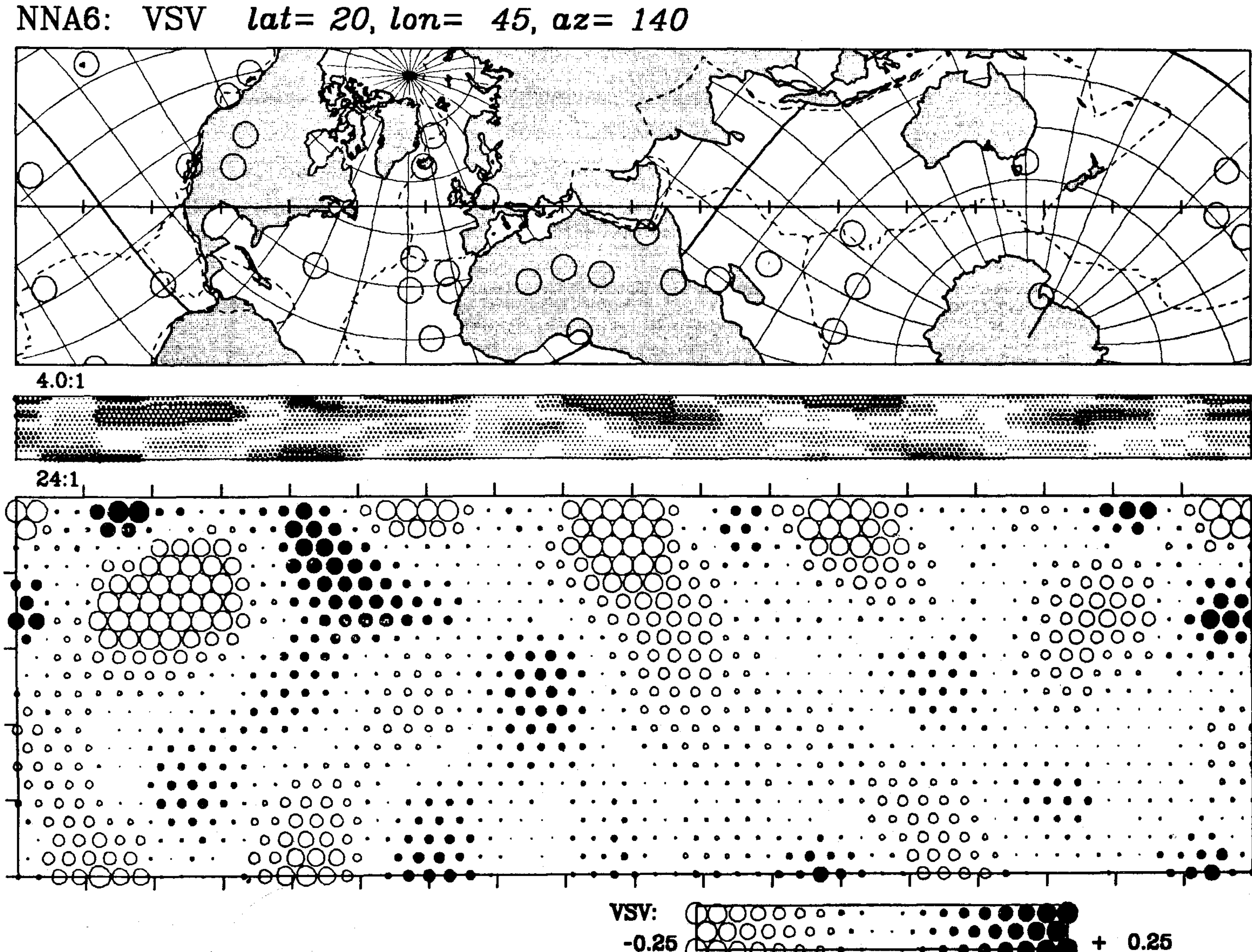

Fig. 4. SV velocity from 50 to 550 km along the great circle path shown. Cross-sections are shown with two vertical exaggerations. Note the low velocity regions in the shallow mantle below Mexico, the Afar and south of Australia and the asymmetry of the north Atlantic. Velocity variations are much more extreme at depths less 250 km than at greater depths. The circles on the map represent hotspots.

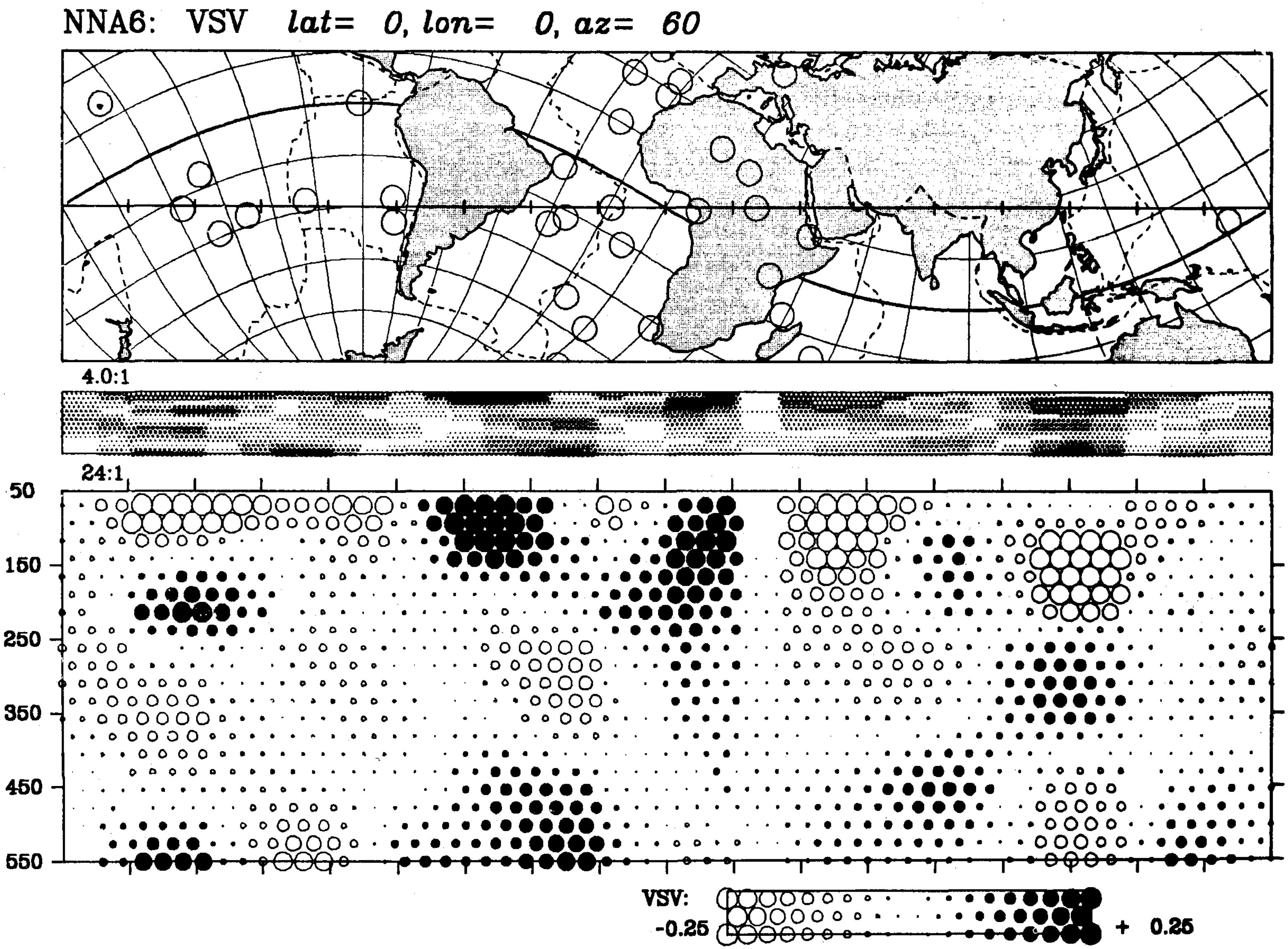

Fig. 5. SV velocity in the upper mantle along cross-section shown. Note low velocities at shallow depth under the western Pacific, replaced by high velocities at greater depth. The eastern Pacific is slow at all depths. The Atlantic is fast below 400 km.

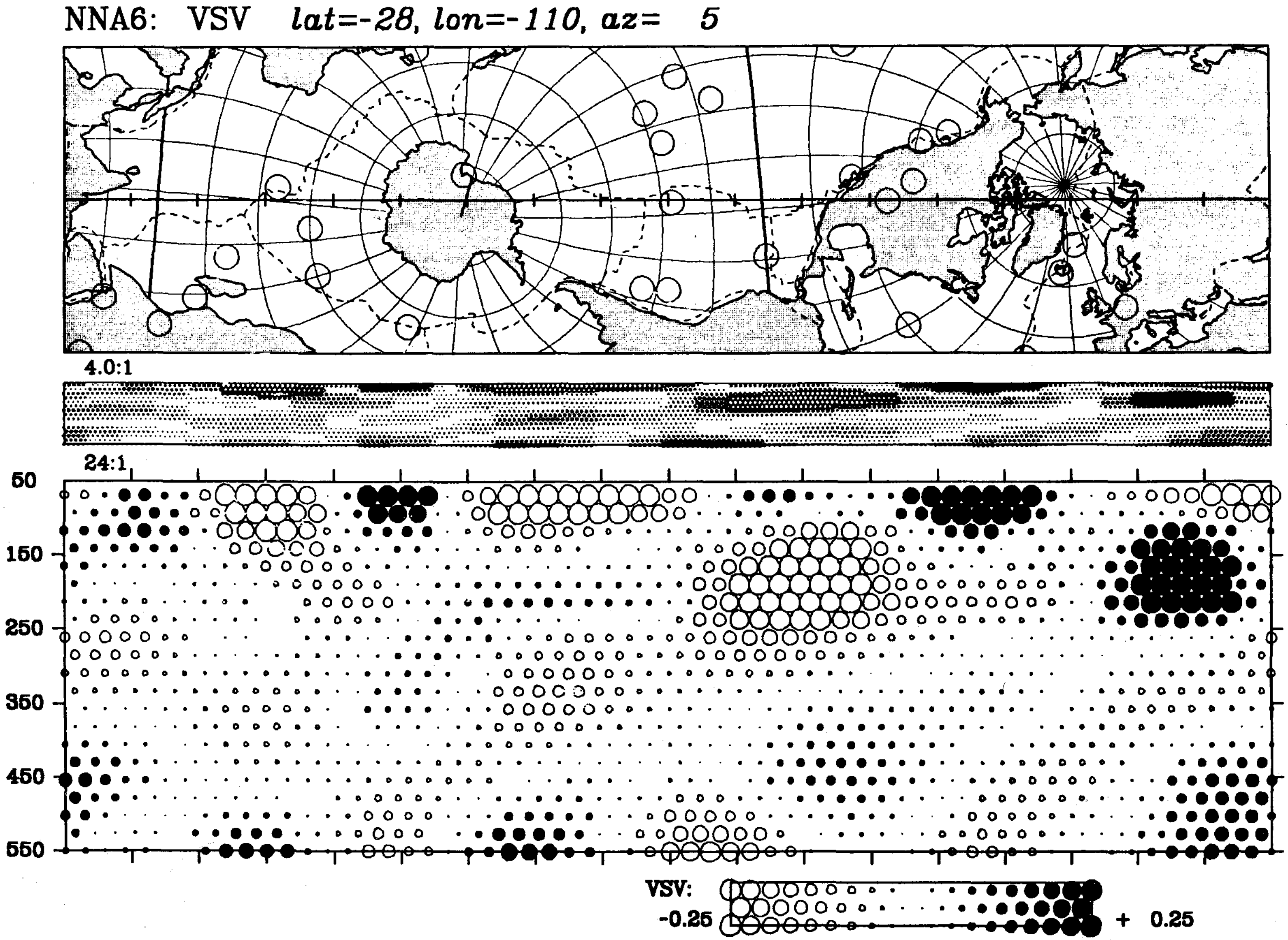

Fig. 6. Cross-section illustrating the low uppermantle shear velocities under midocean ridges and western North America. Stable regions are relatively fast in the shallow mantle.

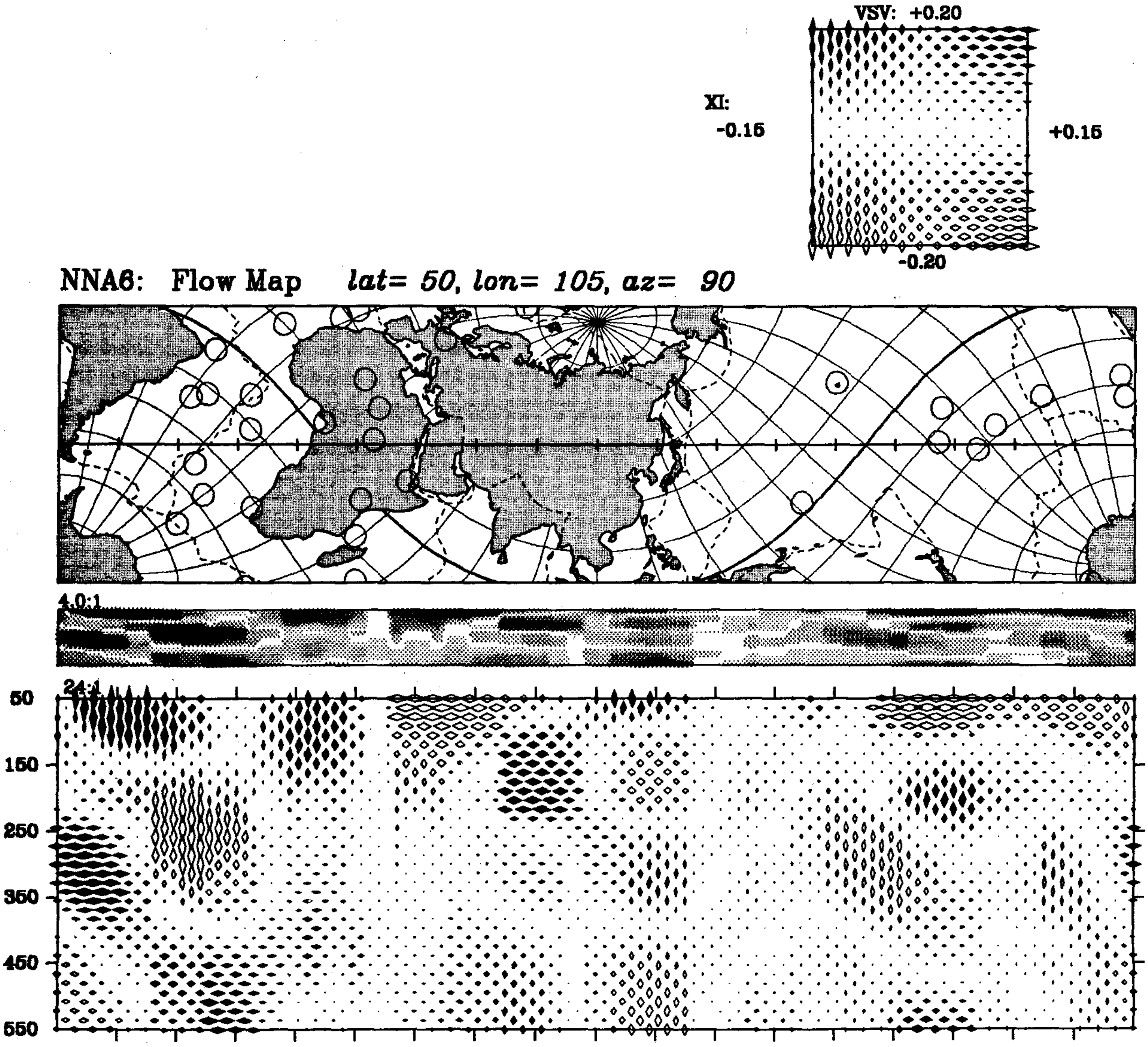

Fig. 7. A cross-section illustrating both velocity (shading of symbols) and anisotropy (orientation of symbols). Upwelling is implied at 300 km under the central Atlantic and central Pacific.

rise, the Indian Ocean Rise and the Red Sea. By combining the velocity and anisotropy information we can infer upwelling at this depth under the midocean ridges, the Red Sea and the Polynesian anomaly, and downwelling under the western Pacific. The slow regions at this depth generally correlate with broad geoid highs. The reversal in the sense of anisotropy as the ridge is approached is consistent with the detailed modelling of the Pacific (Regan and Anderson, 1984).

At 340 km depth (Fig. 2) the Polynesian, Red Sea and most midocean ridge anomalies still persist; the shield areas are no longer evident. Some ridges are fast at this depth, particularly the Australian-Antarctic ridge and the central Atlantic ridge. This may indicate that the ridge system involves lateral transport at shallow depth. Generally, however, the source for midocean ridges appears to extend below 350 km depth.

At 450 km the pattern seen at shallow depths changes dramatically. The mantle beneath most ridges is fast. The Polynesian Anomaly, although shifted, is still present. Eastern North America and/or the western North Atlantic are slow. Most of South America, the south Atlantic and Africa are fast. The northcentral Pacific is slow. Most hotspots are above faster than average portions of the mantle at this depth. The fast regions under the Atlantic, western North America, the western Pacific and south of Australia may be sites of subducted or overridden, oceanic lithosphere. Below 450 km there is little resolution but the general pattern seems to persist. Prominent slow anomalies are under the northern East Pacific Rise and in the northwest Indian Ocean. The central Atlantic and the older parts of the Pacific are fast.

The seismic velocity and polarization anisotropy can be combined into what we call a "seismic flow map". Fig. 3 is one example.

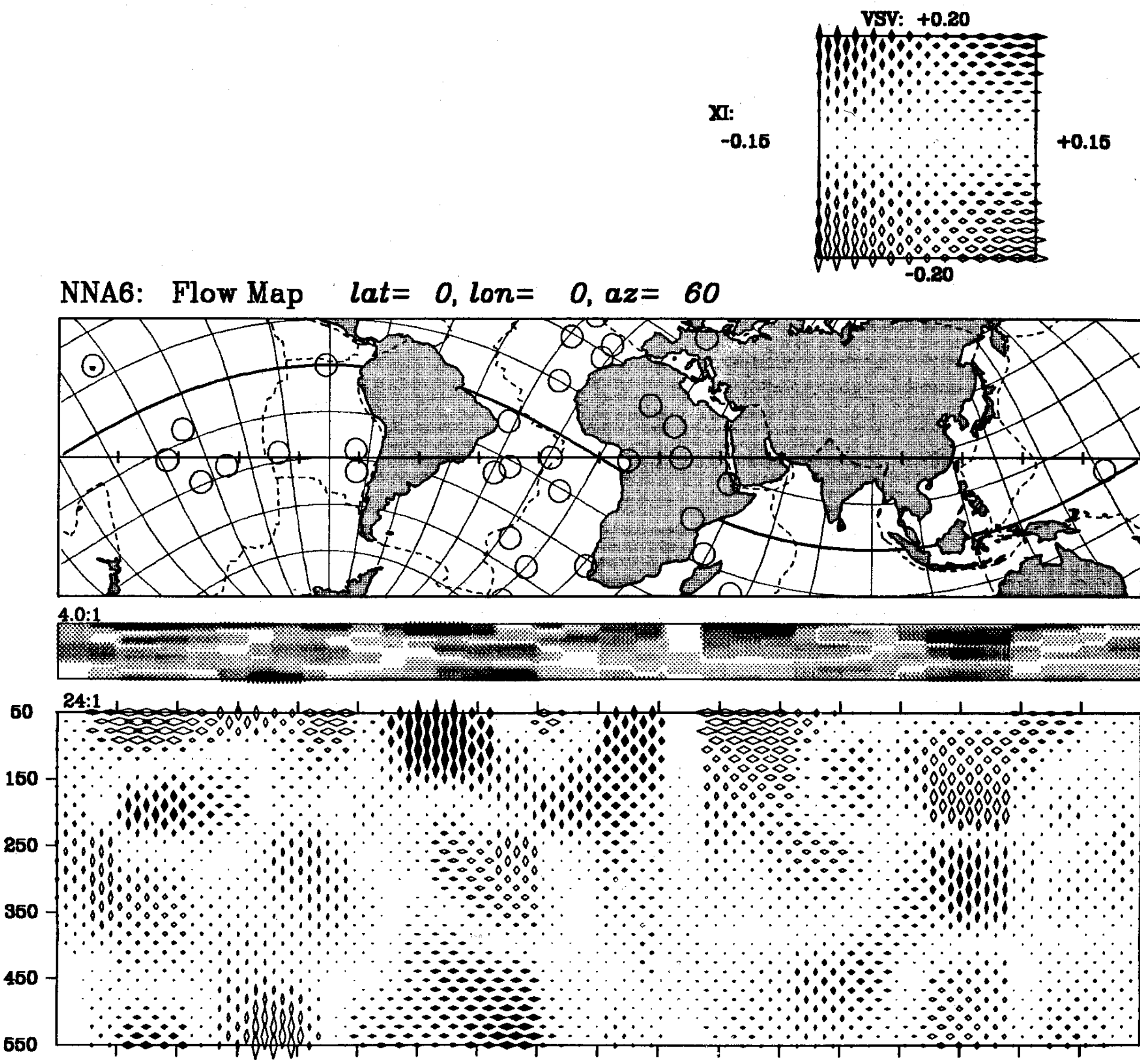

Fig. 8. Upwelling is implied at shallow depths (<250 km) under the Philippine Sea Plate. Downwelling is implied at greater depth, deepening to the west.

Cross-sections

A series of cross-sections are shown in Fig. 4 through Fig. 8. These represent the uppermantle along the complete great circles shown in the top parts of the figures. Full explanations are given in the figure captions.

Azimuthal Anisotropy

Tanimoto and Anderson (1984, 1985) have been able to construct global maps of azimuthal anisotropy from long-period surface wave data. The fast directions for Rayleigh waves are generally at high angles to rises and subduction zones. Preferred orientation of olivine crystals with a consistent alignment over large areas is one explanation of these results. The orientation of the anisotropy appears to be more consistent with theoretical return flow directions in the uppermantle than the plate motion vectors. Regions of relatively low anisotropy may represent stagnation points, points of diverging or converging flow. These occur in the north Atlantic, north America, near Hawaii and Borneo and in the northwest Indian Ocean. Anisotropy, and presumably sublithospheric flow is EW in the north Pacific, NS in the south Pacific and central Asia and NE-SW under Australia and Brazil. Azimuthal anisotropy combined with polarization anisotropy and lateral heterogeneity promises to provide a strong constraint on mantle convection.

Discussion

The inversion of great circle and small arc surface wave dispersion data makes it possible to put higher resolution, but regional, body wave data into a global context. There is general agreement between these studies and the early surface wave studies of Toksöz et al (1967) and Anderson (1966). Shields are characterized by very fast velocities in the upper 150 to 200 km of the mantle with slightly higher than average velocities extending to 400 km. The high velocities between 200 and 400 km probably represent the absence of melting rather than a rigid root. The oceanic mantle is characterized by a shallow and pronounced low-velocity zone and low velocities extend to 400 km. Tectonic regions are also characterized by slow velocities to great depth (Anderson, 1966). Regions of present and former subduction show up as fast anomalies in the transition region. A distinct advantage of surface waves is that polarization and azimuthal anisotropy can be mapped on a global basis.

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