Tectonic Layering of the Lithosphere

by Sergey V. Ruzhentsev and Vladimir G. Trifonov

An important and probably global feature of the lithosphere is the existence of large-scale tectonic layering. This results from differential movements and deformation within specific layers, being most pronounced in ancient fold and recent orogenic belts. The authors discuss methods for detecting this tectonic layering, and its role in the formation of regional structures, with examples from the U.S.S.R. and some neighbouring countries.

Introduction

The concept of plate tectonics, which involves the interaction of rigid, lithospheric plates moving over or together with the asthenosphere, has provided explanations for many features of the morphology, distribution and evolution of crustal structures. However, this theory does not seem sufficient. It has been proved, for example, that plates are not at all rigid, but rather suffer deformation and distortion especially along their margins as they move. Within relatively short periods of time (millions to tens of million of years), plate boundaries may display signs of jumping. This phenomenon, first discovered in spreading zones, also occurs in zones of plate convergence and compression such as the Pamirs, the eastern Taurus and Kamchatka, and in zones of reciprocal plate shear such as western North America.

The existence of differential lateral movements of the lithosphere was demonstrated by A.V. Peive (1967). Further

elaboration of this concept led to the concept of a tectonically layered lithosphere (Makarov *et al.*, 1974; Knipper and Ruzhentsev, 1977; Peive, 1980, 1982; Peive *et al.*, 1983). This theory holds that layers of the crust and upper mantle do not constitute single thick plates, but move reciprocally and suffer independent and unconnected deformation.

The evidence for the tectonic layering of continental fold belts is provided by overthrusts resulting from décollement and displacement of rock bodies relative to their basement. Décollement could have taken place at different levels within the sedimentary cover, along the contact between the basement and the cover, or even within the basement itself, as shown by allochthonous sections. The presence of isolated allochthons in a major structure is related to a regional décollement at the level of the deepest formations of the allochthon complex. Décollement of the sedimentary cover, first described early this century for the Alps, has been shown to be common in many fold areas. Isolated slabs commonly show evidence of displacement of some tens of kilometers. Overthrusts of the basement are larger and rarer, but their displacement range is measured in hundreds of kilometers.

The Pamirs

The Central Pamirs contain four nappe complexes each characterized by different rock assemblages: 1) limestones, volcanics and terrigenous Upper Cretaceous-Palaeogene rocks; 2) a predominantly terrigenous Triassic-Lower Cretaceous sequence; 3) a terrigenous-carbonate Cambrian-Permian sequence; and 4) Precambrian gneisses, schists, quartzites and marbles. The first three décollement levels were part of the sedimentary cover, while the fourth was within the basement.

More deep-seated metamorphic rocks have been recorded from the southwestern Pamirs. At the base are plagiogneisses, plagiomigmatites, quartzites and marbles of the Goran complex (Fig. 1). These are overlain by the Shakh dara complex, the lower part of which (the Khorog unit) is composed of hornblende plagiogneisses and plagiomigmatites with numerous boudins and lenses of eclogite-like rocks, acid granulites, metagabbroids and ultrabasites with garnet and spinel. The contact between the Goran and Shakh dara complexes is marked by a thick (several hundred meters) mylonite zone. The plagiogneisses of the Shakh dara complex are covered by Precambrian gneisses and by Palaeozoic and Mesozoic rocks, which have been contact metamorphosed by abundant Mesozoic granites. Further up the section are truncated Phanerozoic deposits displaced independently from the basement. The Goran and Shakh dara contact zone, now curved and tracing the dome of the southwestern Pamirs, is an overthrust that doubles the granite-metamorphic layer of the region. As judged from the composition of the Khorog

Figure 1: Profiles across the southwestern Pamirs, according to A.A. Belov, A.L. Knipper and S.V. Ruzhentsev (*in* Peive, 1980). Inset shows locations of Figs. 1, 2, 3 and 5.

Figure 2: Geological section of the eastern Koryak Ridge (above) and a palinspastic profile for the late Campanian early Maastrichtian (below), according to S.V. Ruzhentsev and S.D. Sokolov (in Peive, 1980). **Ophiolitic complex:** **a** – dunites, harzburgites and thersolites; **b** – serpentinites and unspecified ophiolites in the upper profile; **c** – layered complex, gabbro, dike complex and plagiogranites; **d** – vol-

canic-siliceous Carboniferous-Permian sequence. **Upper Jurassic-Campanian complexes:** **a** – tuffaceous-terrigeneous complex (Upper Jurassic-Campanian); **b** – the same with basalts and jasperoid rocks (Campanian); **c** – the same with Upper Jurassic-Campanian olistostrome; **d** – greywackes (Volgian – Upper Cretaceous). Roman numerals indicate tectonic zones.

unit, the décollement site must have been located within the lower part of the crust and, probably, at its base. Inside the isolated slabs there are gigantic rootless recumbent folds (Peive, 1980).

The process of décollement and crustal motion in the southwestern Pamirs must have lasted a long time, spanning several tectonic epochs. However, most studies have concentrated on the late Cenozoic deformation associated with the northward motion of India relative to the neighbouring parts of the Alpine-Asian orogenic belt. Comparison of the times of the most extensive thrusting and folding in parts of the Pamir-Karakorum region and the ages of offset in different segments of the wrench fault zones, bordering the region to the west and northeast, has proved that the northern front of the moving lithospheric mass migrated repeatedly northward (see Plate Boundary Map on page 43, this issue – Ed.). In the Oligocene it was situated in the Indus zone, the Miocene saw it in the central Pamirs, in the Late Miocene and Pliocene it was to be found near the Karakul thrust of the northern Pamirs, and finally, in the Pleistocene it was located on the southern slope of the Alay valley.

The mechanics of this migration may have worked as follows. As the Indian plate moved northward, a part of the inner zone of the orogenic belt in front of it became involved in extensive folding and nappe deformation. This led to the isolation of the deformed area at its sides by wrench faults, which represent parts of the Chaman-Darvaz-Alay and Pamir Karakorum fault systems, and probably to the décollement of the deformed and faulted crustal masses. As a result, the latter could no longer be seriously deformed, and they joined and moved together with the margin of the plate, while the zone of extensive displacement that marked the front of the moving masses jumped to the north. This process was repeated until the structure in the Karakorum and Pamirs became a series of stacked thrust mega-sheets with a complex inner structure, and structurally isolated from more deep-seated layers of the lithosphere (Trifonov, 1983).

The Urals

Large nappes of the basement of the Urals typically show the following upward sequence of rocks (Peive, 1980; see also

Dymkin and Puchkov, this issue of Episodes – Ed.):

- dunites and harzburgites of the mantle,
- pyroxenites, dunites and gabbroids representing a transitional zone between the mantle and crust
- gabbroids partially converted to amphibolites
- gabbro-diabases, diabases and plagioliparites of a dike complex
- quartz diorites and plagiogranites
- volcanic-sedimentary deposits.

Such ophiolitic allochthons containing dunite-harzburgite rocks demonstrate that, at least in the palaeo-oceans, regional décollement could penetrate the upper mantle.

The Koryak Ridge

The Koryak ridge at the base of the Kamchatka peninsula in the northeastern U.S.S.R. features two stages in nappe formation (Fig. 2), related to the readjustment of the late Palaeozoic structural pattern and the development of a back-spreading frontal-thrust system with pronounced pre-Maastrichtian movements (Peive, 1980). The main spreading of the back trough, together with the exposure of the melanocratic basement, began at the close of the Late Jurassic and continued in the Cretaceous. At the same time, the frontal basin was filled by deposits from the destruction of ophiolitic allochthons moving towards it. In terms of crustal type, structural position and type of sedimentation, the back trough is comparable to newly formed basins of marginal seas. Décollements took place near the Moho discontinuity and also within the crust, dividing it into a series of independently moving slabs.

As shown by the Koryak ridge, décollement of crustal slabs is found not only in areas of compression but also in zones of ocean-floor spreading. The formation and spreading of the oceanic crust was due to the injection of basaltic material along numerous fractures to form dike series. Using examples of ancient oceanic formations in the Urals, Western Sayan and Mongolia, A.S. Perilyev and N.N. Kheraskov (in Peive, 1980) have shown that dikes and occasionally the magmatic breccias which accompany or replace them saturate the lower gabbroid-ultrabasite part of the crust, though they decrease sharply in the underlying, intensely folded

Figure 3: A schematic section through the Kurtushiba ophiolitic complex in the Western Sayan, according to A.S. Perflyev and N.N. Kheraskov (in Peive, 1980).

dunite-harzburgite layer of the upper mantle (Fig. 3). The ancient crustal spreading appears thus to have taken place in the crust independently of the upper mantle. The bottom of the dike and breccia zone often exhibits sills intruded along the décollement surfaces of the spreading crust and probably formed as a result of heating during sliding.

Figure 4: Relation between the Western Tien Shan zone of flexure and faulting and modern seismic activity of Uzbekistan, according to B.B. Tal-Virsky and others (in Peive, 1982). Seismic activity shown as contours of equal energy release according to the Riznichenko method where contour values represent the logarithm of the number of earthquakes with energy class, $K = 9.5-10.6$, where $K = \log E - 7$ and E is the seismic energy of the earthquakes. Numbers in epicenters indicate the energy class, K .

Recent Tectonic Layering

Examples given above are typical of ancient folded belts, where deep-seated zones of décollement and differential lateral movement were subsequently brought to the surface and exposed for study. However, what is important for tectonic theory is whether similar processes exist in modern geological times, when we can reconstruct displacements of the surface on a global scale and for which we have seismic data on movements within the deep-seated lithospheric layers.

There is certainly indirect evidence of recent tectonic layering, which comes from the combined application of geological, structural, geomorphological and geophysical methods (Makarov et al., 1974; Peive, 1980). The neotectonics of orogenic areas show, along with dominant structures such as longitudinal fold-ridges and escarpments, transverse and discordant elements discernible on the surface such as weak flexures, extensive jointing, and the closure of some ridges and valleys. Seismic data on the geometry of focal zones and zones of abnormal propagation and absorption of seismic waves make it possible to differentiate modern structures according to the depth of their greatest development.

Satellite imagery also aids greatly the detection and mapping of deep-seated elements discordant to the general surface trends. Such structures are sometimes expressed by neovolcanic and hydrothermally active zones, as well as by hydro- and geochemical anomalies. The comparison has revealed that obscure surface structures can be more pronounced at depth, and that those prominent on the surface can be limited at depth by the sedimentary or granitic-metamorphic layers. Therefore, modern structural patterns in the lithosphere also differ by depth levels, indicating independent neotectonic development of lithospheric layers and their disharmonic movement.

Geological, geomorphological, geophysical and satellite data on the eastern Caucasus demonstrate that the crust here has three structural levels where fault zones and deformation of different morphology and trends have developed simultaneously in modern times. The upper level, occupied chiefly by the sedimentary cover, is dominated by folds and thrusts with the usual Caucasus trend. Below this, at depths of about 20 km, this structural trend is represented only by a seismically active zone of upthrows and thrusts, which is the deeper extension of the southern slope of the Great Caucasus; of importance in this middle level are shorter shear zones with oblique strikes that are poorly reflected in the upper structural level. The density of shallow earthquakes increases along these zones, which are surrounded by regions of abnormal seismic absorption. Associated with these shears are gravity-gradient zones and, to a limited extent, structural elements of the surface of the pre-Jurassic crystalline basement and the Conrad discontinuity. Further downward and reaching the Moho discontinuity, is the continuation of the southern slope of the Great Caucasus, which must become steeper deep in the crust. It concentrates the deepest earthquakes of the region and shows a sharp variation in the thickness of the Earth's crust (from 50 to 60 km in the north to 40 to 45 km in the south).

These signs of structural disharmony may be related to different responses to the general north-south compression of the region. The crustal structures of the Caucasus are crossed by volcanic and related tectonic elements of the Transcaucasian volcanic belt which, according to E.E. Milanovsky, reflect east-west extension and magmatism in the upper mantle portion of the lithosphere. Chains of volcanoes and faults of this belt extend through all the region, suggesting that the structural and dynamic setting of the upper mantle of the Caucasus and Transcaucasus is radically different from that of the crust.

Significant vertical variations have been described in modern structures of the Tien Shan and the adjacent Turanian plate (Makarov *et al.*, 1974; Peive, 1982). At depth, modern folds of the basement are combined into larger structural forms, and transverse and diagonal elements, usually not pronounced in the upper structural level, become more important. An example of these elements is provided by the NE-SW plutonic zone of flexures and faults in the Western Tien Shan (Fig. 4). This corresponds to a significant and extended gravity gradient zone. The crustal thickness increases here from 40 km to the west of the zone to 50 km to the east, and there are also changes in seismic activity, focal mechanisms, and the morphology of the anomalous magnetic field. The Western Tien Shan zone preserves for a considerable distance along strike its anomalous seismic absorption.

Evidence from Seismology

Seismic surveys that detect horizontal focal zones and crustal waveguides provide additional evidence of tectonic layering in the lithosphere. Detailed studies of vertical and tilted focal zones within the continents and on their margins have shown that such zones often have a large-scale beaded structure, wide in one part and narrow in the other or disappearing altogether in other levels of the crust and the upper mantle. The Kuril-Kamchatka focal zone, for example, consists of separate peaks of activity, which are interrupted at depths of approximately 80, 120-160, 220-300 and 340 km, by horizons of increased absorption of seismic energy (Anon, 1976).

According to Yu.K. Shchukin (in Belousov *et al.*, 1979), this heterogeneity is even more pronounced in the Pamirs-Hindu Kush focal zone (Fig. 5). Here at depths of 40 ± 10 km there is a horizontal zone of hypocenter concentration, which may be a recent manifestation of the demonstrable modern décollement of upper crust structures. This region is underlain by a hypocenter-poor layer above a steeply dipping mantle focal zone. The latter is regarded as a modern deep-seated boundary of the Indian plate, which projects onto the surface somewhere in the Central Pamirs, though the seismic peak in the upper-crust is 150 km farther north. The hypocenters of the upper crust are more common in the south-dipping zone, which, if continued up to the surface, would coincide with the Darvaz-Alay fault zone, the recent boundary of the Indian plate in the upper crustal layer (Trifonov, 1983).

The crust below the Pamirs and Karakorum is up to 70 km thick (Belousov *et al.*, 1979). V.K. Kulagin (in Peive, 1982) has singled out crustal waveguides at depths of 5-18 and 30-43 km. Waveguides have now been detected both inside and at the base of the crust below various active and passive recent structural zones (Fig. 6) such as the Caucasus, the Urals, the Baikal rift zone, Precambrian shields and other continental and oceanic structures (Peive, 1982; Trifonov, 1983). Waveguides are subhorizontal, lenticular zones of low seismic velocity, which may be due to lower effective viscosity and strength of the rocks. Thus, décollements of relatively viscous and solid rock bodies are to be expected along the waveguides in a specific tectonic setting. Such décollements have been proved in some orogenic areas, such as the Pamirs, by the partial coincidence of waveguides and horizontal focal zones. The low effective viscosity of these wave guides may be a result of a seismically induced loss of rock strength (Yu.K. Shchukin in Belousov *et al.*, 1979).

Unevenly distributed hypocenters in vertical and tilted focal zones suggest a vertical, structural and dynamic heterogeneity of more deep-seated lithospheric layers. The existence of such heterogeneity is demonstrated by recent studies of the differences in relative values of shear stress, seismic deformation rates and effective seismic viscosity in different levels of mantle focal zones. This analysis, by F.A. Vostrikov, is based on the interpretation of plots of earthquake recurrence. The mantle focal zone of the Pamirs and Hindu Kush shows two layers with exceptionally low values of

Figure 5: Seismicity of the lithosphere of the Tien Shan and the Pamirs-Himalayas. Shown above is the Bouguer gravity anomaly curve (Belousov *et al.*, 1979). Contours indicate density of concentration of earthquake hypocenters. Horizontal scale approximately 1:9 250 000. Vertical exaggeration = 1.75.

seismic viscosity at depths of 70-100 km and 130-150 km. The acting stress is also low in these layers, perhaps as a result of higher plastic deformation. Rates of seismic deformation (rupturing) decrease in the lower and in part of the upper low viscosity layers and increase at depths of some 70 km.

A.V. Nikolayev and I.A. Sanina (1982) have analysed differences in the travel times of seismic waves of local deep-focus earthquakes detected by Central Asian stations. This has led to the discovery of broad lateral and vertical varia-

Figure 6: Averaged crustal velocity sections for (a) the Southern Tien Shan, (b) the Tadjik basin and (c) the Pamirs according to V.K. Kulagin (in Peive, 1982).

tions in seismic rates in the upper mantle of the Afghan-Tadjik basin and the Pamirs at depths of up to 300 km. In contrast to the northern parts of this region, where the distribution of seismicity is in agreement with a layered model, in the vicinity of the Pamirs-Hindu Kush focal zone and southward there is a more complex distribution of seismic rates. This may reflect differential movements of mantle rock bodies no less complex than those in the crust.

Discussion

Thus, abundant data indicate that in ancient and modern orogenic belts, rock bodies of the crust and upper mantle interact not as rigid plates with lithospheric thicknesses, but rather as a complex of relatively thin rigid slabs and blocks separated by zones of high-gradient lateral movements (asthenolayers and asthenolenses). Similar signs of structural and dynamic layering in the lithosphere have also been discovered in rift systems and shear belts. However, the disharmony between different layers of the lithosphere is not absolute. Certain links between them are preserved and permit deep-seated neotectonic structures to be reflected in the topography and deformation of the surface, where they can be identified from space images.

Whether or not tectonic layering extends across the boundaries of geologically active regions cannot be determined as yet. However, as outlined above, one possible approach to this problem is to determine rates of lateral movements of different slabs of the same plate relative to those in adjacent ones. For example, the average convergence rate for India and Eurasia, according to Quaternary fault displacement and fold deformation in the area of their interaction, is 3-5 cm per year (Trifonov, 1983). However, analyses of oceanic anomalies indicate that the rate of the motion of the Indian Ocean floor relative to the Eurasian plate reaches 5-6 cm per year. It is possible, therefore, that the upper mantle and thin oceanic crust of the Indian Ocean are converging with Eurasia more rapidly than the Indian continental crust.

These and other considerations lead to the conclusion that differential movements of lithospheric slabs along asthenolayers and asthenolenses are global, though distributed unevenly from region to region. It is not these differential movements that are important in controlling regional structures but rather the change in their relative rates, which results either in piling-up of rocks or in spreading and injection of plutonic differentiates. It is such regions that are interpreted as active and in which tectonic layering is most pronounced.

The concept of tectonic layering provides a new approach to many problems of tectonics. For example, it is hardly possible to explain the structural consequences of Indian and Eurasian convergence as mere subduction. Instead there is a piling-up of rock here due to differential movements and independent deformation at different levels in the lithosphere. The shortening is complemented by squeezing-out of rock masses away from areas where lithospheric slabs are most compressed.

This model of tectonic layering contributes also to our understanding of isostatic compensation. We should take into account possible fractional melting in asthenolayers if we want to explain regional granitoid magmatism and formation of contrasting volcanic complexes. Irregular layering in the lithosphere and differences in rates of motion and deformation of the slabs could have led to their destruction and mixing, accompanied by chemical change, fractional melting and gravitational differentiation. This mechanism should also be taken into account in metallogenic and hydrocarbon studies, for allochthonous granitic-metamorphic masses may conceal undiscovered oil and gas fields. Analyses of the recent activity of some crustal zones of lateral sliding, especially where areas of different structural trend make contact, also open up new prospects for the prediction of seismic risk.

References (Those not in Russian are asterisked)

- Anon., 1976. Structure of the Earth's crust and upper mantle in the transition zone of the Asian continent and the Pacific. Nauka, Novosibirsk, 368p.
- Belousov, V.V. et al., 1979. Structure of the lithosphere according to the deep seismic sounding of the Tien Shan - Pamirs-Karakorum-Himalayas. *Sovetskaya geologiya*, no. 1, p. 11-27.
- Knipper, A.L. and Ruzhentsev, S.V., 1977. Deep faults and the geosynclinal process. In: *Faults of the Earth's crust*. Nauka, Moscow, p. 8-19.
- *Makarov, V.I., Skobelev, S.F., Trifonov, V.G., Florenskiy, P.V. and Shchukin, Yu.K., 1974. Plutonic structure of the Earth's crust on space images. In: *Proceedings of the Ninth International Symposium on Remote Sensing of Environment*, vol. I, Ann Arbor, Michigan, p. 369-438.
- Nikolayev, A.V. and Sanina, I.A., 1982. Method and results of seismic investigation of the Tien Shan and Pamirs lithosphere. *Doklady Akademiy nauk. SSR*, vol. 264, no. 1, p. 69-72.
- *Peive, A.V., 1967. Faults and tectonic movements. *Geotectonics*, no. 5, p. 268-275.
- Peive, A.V. (ed.), 1980. Tectonic layering of the lithosphere. *Trudy Geologicheskii institut, Akademiya nauk SSR*. Nauka, Moscow, 216p.
- Peive, A.V. (ed.), 1982. Tectonic layering of the lithosphere of neotectonic active belts. *Trudy Geologicheskii institut, Akademiya nauk SSR*. Nauka, Moscow, v. 359, 192p.
- *Peive, A.V., Ruzhentsev, S.V. and Trifonov, V.G., 1983. Tectonic layering and problems of the continental lithosphere. *Geotectonics*, v. 17, p. 1-8.
- Trifonov, V.G., 1983. Late Quaternary Tectonics. Nauka, Moscow, 224p.

Dr. S.V. Ruzhentsev is a senior scientific researcher at the Geological Institute of the Academy of Sciences (7 Pyzhevsky, Moscow, 109017). His works are devoted to problems of overthrusting and formation of the continental crust in the Pamirs, the Urals, the Koryak Ridge and elsewhere.

Dr. V.G. Trifonov is head of the Laboratory of Neotectonics and Remote Sensing of the Geological Institute in Moscow. His main research concentrates on remote sensing, neotectonics and recent geodynamics in regions such as the Caucasus, Central Asia, Mongolia, Iceland, and western U.S.A.