RUSSIAN JOURNAL OF EARTH SCIENCES, VOL. 4, NO. 1, PAGES 19–33, FEBRUARY 2002

A gravity model of the north Eurasia crust and upper mantle: 2. The Alpine-Mediterranean foldbelt and adjacent structures of the southern former USSR

M. K. Kaban

Schmidt United Institute of Physics of the Earth, Russian Academy of Sciences, (UIPE RAS), Moscow

Abstract. A density model of the lithosphere for the Caucasus, Kopet-Dagh, a part of Tien-Shan, Caspian and Black seas, as well as for adjacent parts of East European platform and Turanian plate is constructed based on an integrated analysis of gravity, seismic refraction and geological data. Joint analysis of the mantle and isostatic gravity anomalies shows that the tectonics in the study area is controlled not only by the continental plate convergence but also by processes in the upper mantle. The residual mantle anomalies in the region are as much as ±170 mGal which correspond to deviations from the average upper mantle density up to ±80 kg/m^3. The minimum mantle density values are found for Eastern Tien-Shan and Lesser Caucasus. The upper mantle under these structures is hot and likely affected by mantle plumes. This conclusion is also in agreement with a local character of the isostatic anomalies. High values of the mantle anomalies correspond to the shields of East Europen platform and the Urals. The amplitudes of the isostatic anomalies reach ±150 mGal in the study area. The most significant isostatic disturbances are found in the northern part of South Caspian (negative) and in the joining to this structure areas of Talysh and Kara-Bogaz swell (positive). These results indicate high stresses within the lithosphere which agrees with the seismicity distribution. The broad negative isostatic anomaly located over the eastern part of the Caucasus foredeep indicates that Skythian plate is elastically deformed and underthrusts the Eastern Caucasus. The same is true for the Turanian–Kopet-Dagh plate system. In the Western Caucasus the situation is opposite: near zero isostatic anomalies over the foredeep evidence that the lithosphere is weak and no significant elastic deformations exist in this area.

Introduction

This work is a follow-up of an earlier companion paper [*Kaban,* 2001], where I analyzed principal regularities of lithospheric density structure beneath northern Eurasia. The area addressed in this study encompasses that part of the Alpine foldbelt located on the former USSR territory and its contiguous tectonic structures from the Black Sea to western offshoots of Tien Shan, including southern segments of the Turan and Scythian plates, the Caucasus, the Kopet Dagh, and the Caspian Sea structures. Compared to the work just mentioned, this study is considerably more detailed, and lithospheric models analyzed here are more complex and better approximate real structures. It was for two reasons that the above area became the focus of my special study. Firstly, it may be unparalleled in terms of intensity and range of tectonic processes occurring there. Hence, our knowledge of the nature of tectonic processes in this region will afford a better insight into the evolution of the lithosphere as a whole. Secondly, a considerable portion of this area was covered in great detail by various geologic and geophysical surveys, which permits more reliable models to be constructed.

Tectonic processes are largely controlled by the evolution of density inhomogeneities in the gravity field, irrespective of the nature of such inhomogeneities, which is the reason why

Paper number TJE02082.
ISSN: 1681–1208 (online)

The online version of this paper was published March 21, 2002.
URL: http://rjes.wdcb.ru/v04/tje02082/tje02082.htm

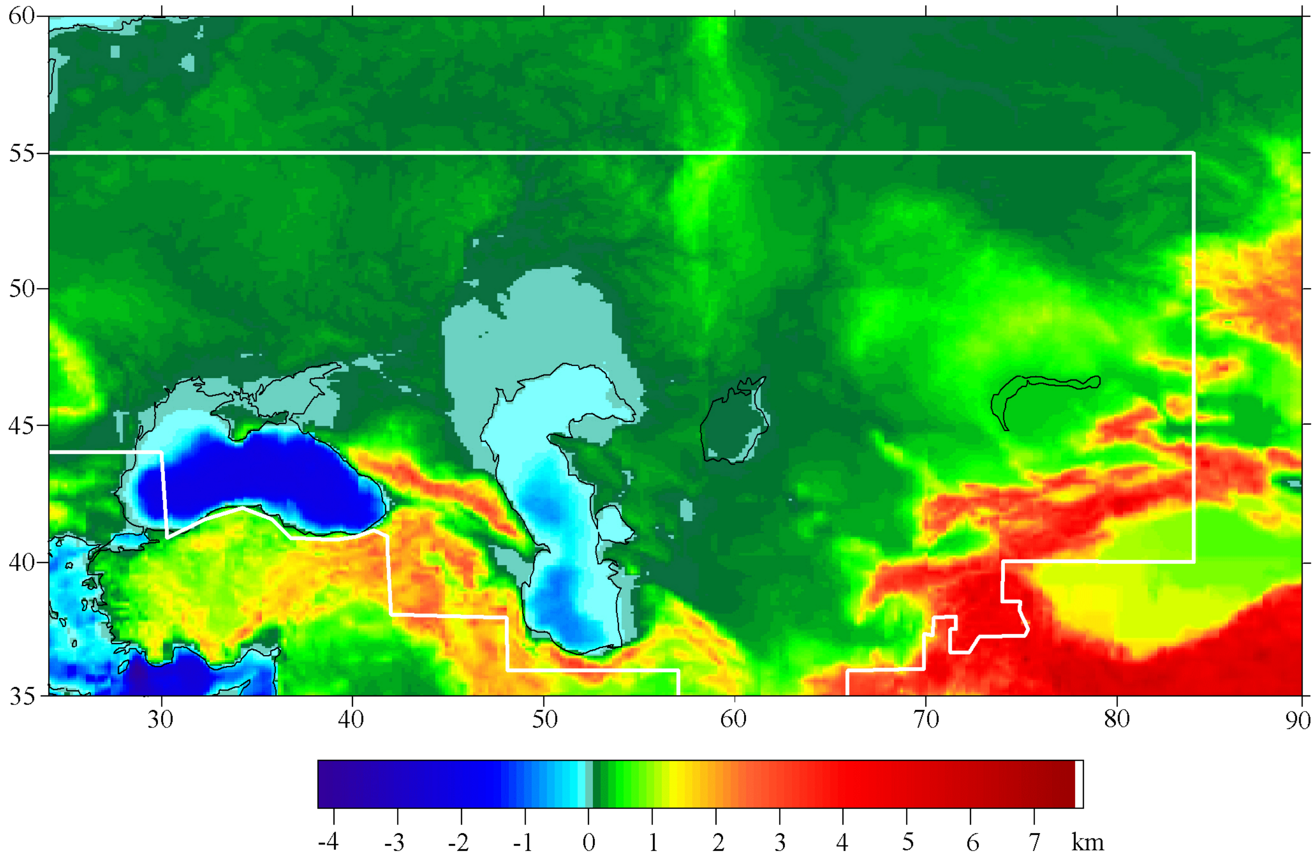

Figure 1. Topographic map.

a gravity model for the region may provide a sound basis for all and any geodynamic constructions. Needless to say, due account should be taken of the existence of external factors, such as regional stresses. Since the 1960s, numerous studies have been dedicated to the analysis, in particular, of gravity data from the southern part of the former USSR, and, as it is virtually impossible to mention all of these works here, note, e.g., the collection of papers in [*The Gravity Model...,* 1979]. Despite the wealth of such studies, no integrated model for the region in point, employing innovative interpretive techniques or, no less importantly, an all-embracing region-wide methodological basis, has been put forward to date. This work embarks on the analysis of such a model, based on generalization of my own studies from particular portions of the region.

Raw data and principal gravity field conversions

Topographic relief and the primary gravity field

The study area is located between longitudes 24°–84°E and latitudes 35°–55°N. These boundaries are defined mainly by the availability of sufficiently detailed and uniform information. Figure 1 shows the topographic relief of the study area and adjacent regions, and the specific area where all the constructions were carried out is outlined with a white line. In the south, this line delimits the area with high resolution gravity coverage. Over a considerable part of the study area (Caucasus, Kopet Dagh, and adjacent regions), resolving power of the raw data is no worse than 10 km by 10 km. Raw gravity data from the Caucasus region are based on detailed Bouguer anomaly maps plotted under B. K. Balavadze's leadership in the Institute of Geophysics of Georgia [*Artemjev et al.,* 1985], and from the east part of the study area, on maps prepared in the Institute of Geology of Turkmenistan [*Artemjev et al.,* 1992; *Kaban et al.,* 1998]. The necessary fitting together of the primary matrices was done using regional gravity data with a resolution of 10′ by 15′, prepared in the Central Research Institute of Geodesy, Aerial Photography, and Cartography [*Artemjev et al.,* 1994]. The primary Bouguer anomaly map is shown in Figure 2.

Crustal density model

At each computation point, depth to basement and sediment density were determined, based mainly on drilling and seismic data, which were used for interpolation to greater

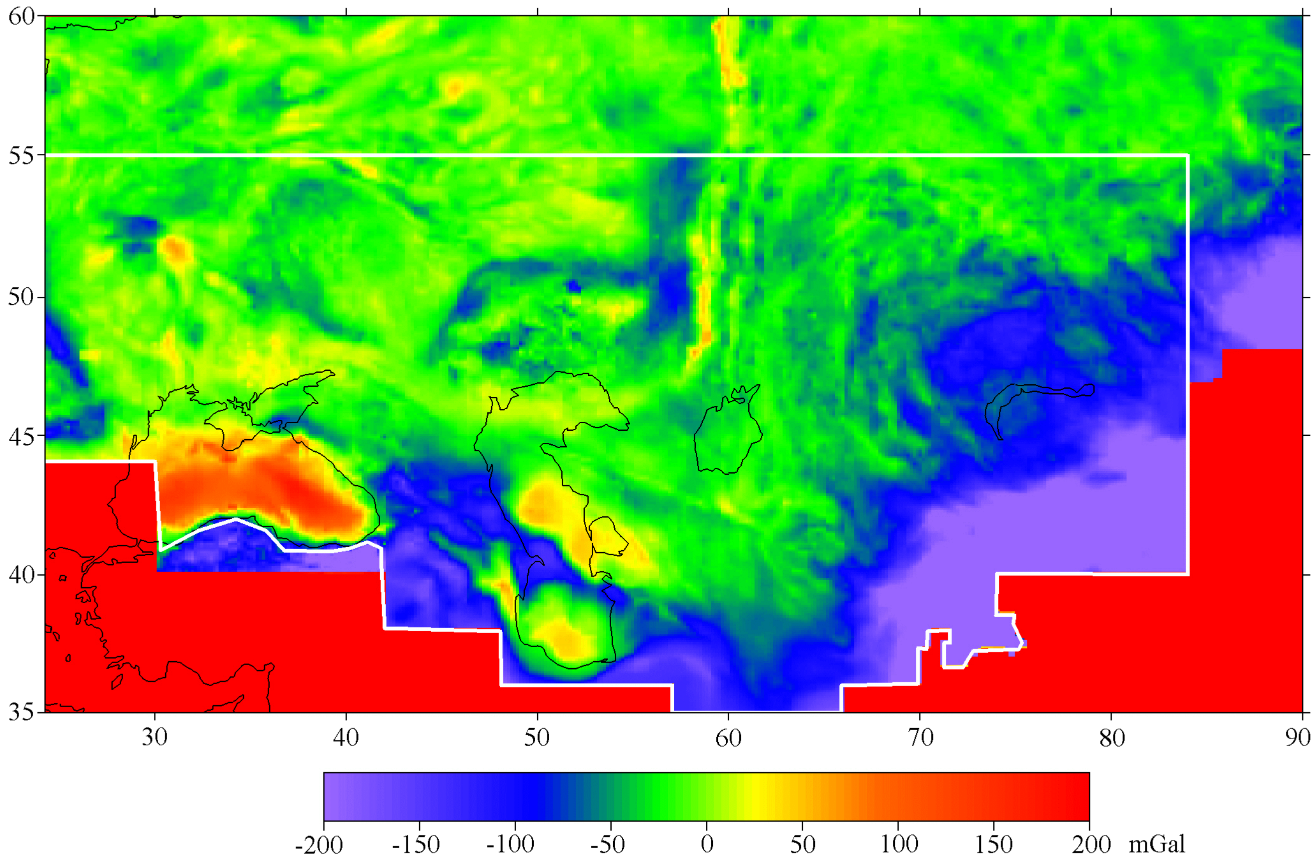

Figure 2. Bouguer anomaly map.

depths. The technique of constructing the density model for sedimentary cover and computing its gravity effect is detailed in the companion paper [*Kaban,* 2001] and in [*Artemjev et al.,* 1985, 1992; *Gordin and Kaban,* 1995; *Kaban et al.,* 1998]. Figure 3 shows a sediment thickness map for the portion of the study area that includes the southern Eastern European craton and the Caucasus and their adjacent sectors of the Black and Caspian seas.

As was discussed repeatedly, the density of sedimentary cover bears even greater implications to gravity constructions than sediment thickness does. The above works summarized density characteristics of sediments, enabling the calculation of their gravity effect across the entire study area, shown in Figure 4. As appears from this figure, the total effect of the anomalous density of sediments is as great as -135 mGal. Because over the southeast part of the study area, including western offshoots of Tien Shan, detailed data are lacking, the field is imaged by the regional model here. By and large, it can be ascertained that the sediment-related gravity field is considerably smoother than the sediment thickness, which is readily apparent from the maps in Figures 3 and 4. This is due to the fact that the largest sediment density anomalies are recorded at depths to 8 km. They are induced mainly by the presence of pores that close rapidly as the pressure increases and the density of sediments becomes similar to that of basement rocks. This is seen clearly from the generalized curves depicting the depth dependency of density in various sedimentary basins, given in the companion paper [*Kaban,* 2001]. Hence, at depths greater than 8 km, sediment thickness variations bear on the gravity field but insignificantly.

Figure 5 shows a composite Moho depth map for the study area. Its base is provided by the regional map from the companion paper, refined somewhat over those local structures where sufficient data are available. Primary information on crustal structure, just as for sedimentary cover, is poorest for Tien Shan. There, only scanty data on converted waves from earthquakes and seismic tomography data [*Kosarev et al.,* 1993] were used. Density inhomogeneities in solid crust are borrowed without changes from the companion paper [*Kaban,* 2001].

Residual and isostatic anomalies

Residual anomalies obtained by removing the gravity effect of crustal layers from primary Bouguer anomalies are shown in Figure 6. These anomalies must reflect the influence of density inhomogeneities in the upper mantle. The calculation technique is the same as in the companion paper [*Kaban,* 2001], but this study is considerably more detailed. In particular, previously, while studying northern Eurasia

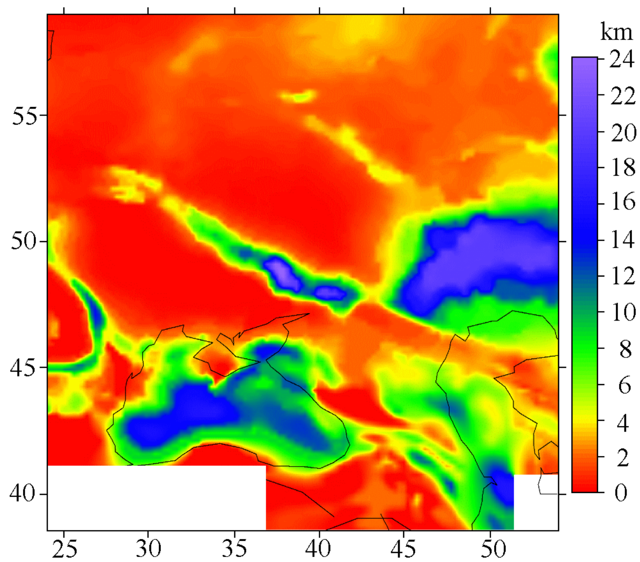

Figure 3. Sediment thickness over the south part of the Eastern European craton, the Caucasus, and adjacent Black Sea and Caspian Sea offshore.

as a whole, it was not possible to identify any dissimilarities between the western and eastern Caucasus or between structures within the Black and Caspian seas, etc.

Of critical importance is assessing the error of identification of mantle gravity anomalies. This problem is analyzed in detail in [*Kaban and Schwintzer,* 2001]. The maximum error can be as large as 50 mGal, although in the best studied areas the error is smaller, ca. 25 mGal. Our analysis of mantle anomalies will make use of the maximum value, i.e., anomalies of less than 50 mGal will be rejected.

Besides, isostatic gravity anomalies, shown in Figure 7, were calculated across the entire study area. The technique used in calculating them is detailed in the companion work [*Kaban,* 2001]. It should only be recalled that, in contrast to previous works, while calculating isostatic anomalies, I used real data on crustal structure, including variations in the thickness and density of sedimentary cover and solid portion of the crust, whereas additional compensating masses, ensuring isostatic equilibrium of crustal structures, are placed in the upper mantle. Depth to the centers of gravity of compensating masses was determined using the cross-spectral technique [*Artemjev and Kaban,* 1994; *Artemjev et al.,* 1994; *Kaban et al.,* 1998]. Departure from Airy's customary scheme leads in many cases to revision of the existing assessments of isostatic equilibrium of crustal structures.

Isostatic anomalies reflect mainly the influence of three factors:

1. Departures from isostasy proper in its local sense, as an artifact of calculations ignoring eventual elastic support to nearsurface load.

2. Lack of due account for density inhomogeneities of sedimentary cover and basement.

3. Departures of the real isostatic compensation scheme from that used for modeling.

The influence of Factors 2 and 3, at least as regards

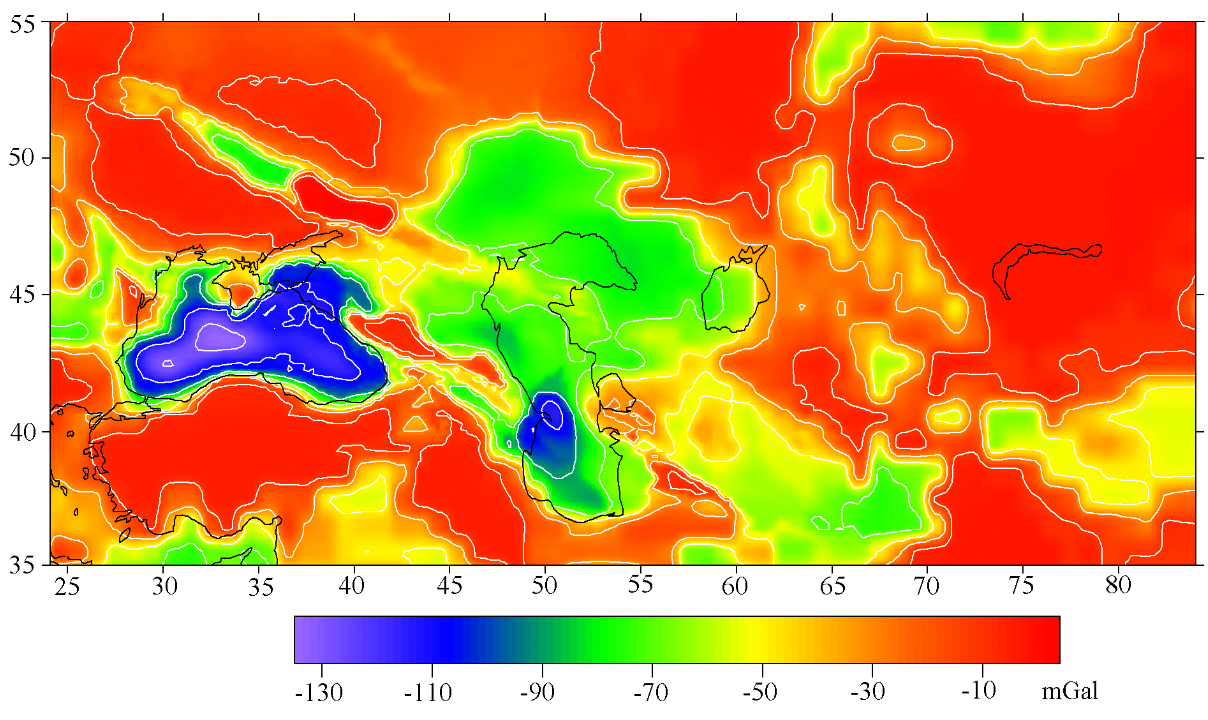

Figure 4. Anomalous gravity field of sedimentary cover.

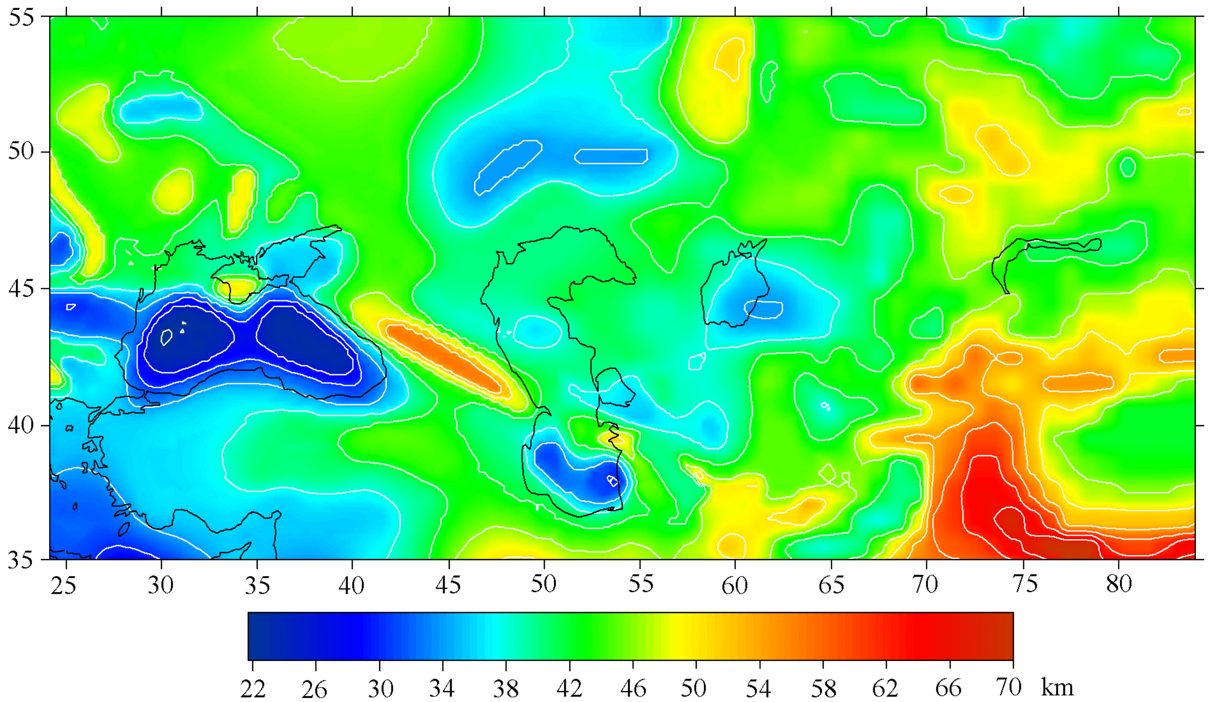

Figure 5. Depth to the Moho discontinuity.

rather large structures, was reduced considerably by taking thorough and detailed account of density inhomogeneities of sedimentary cover and by choosing an effective compensation model. Hence, anomalies obtained in this work can be termed "isostatic" proper on much more solid ground than in many previous studies. The distribution pattern of these anomalies must be related largely to the character, polarity, and intensity of tectonic processes.

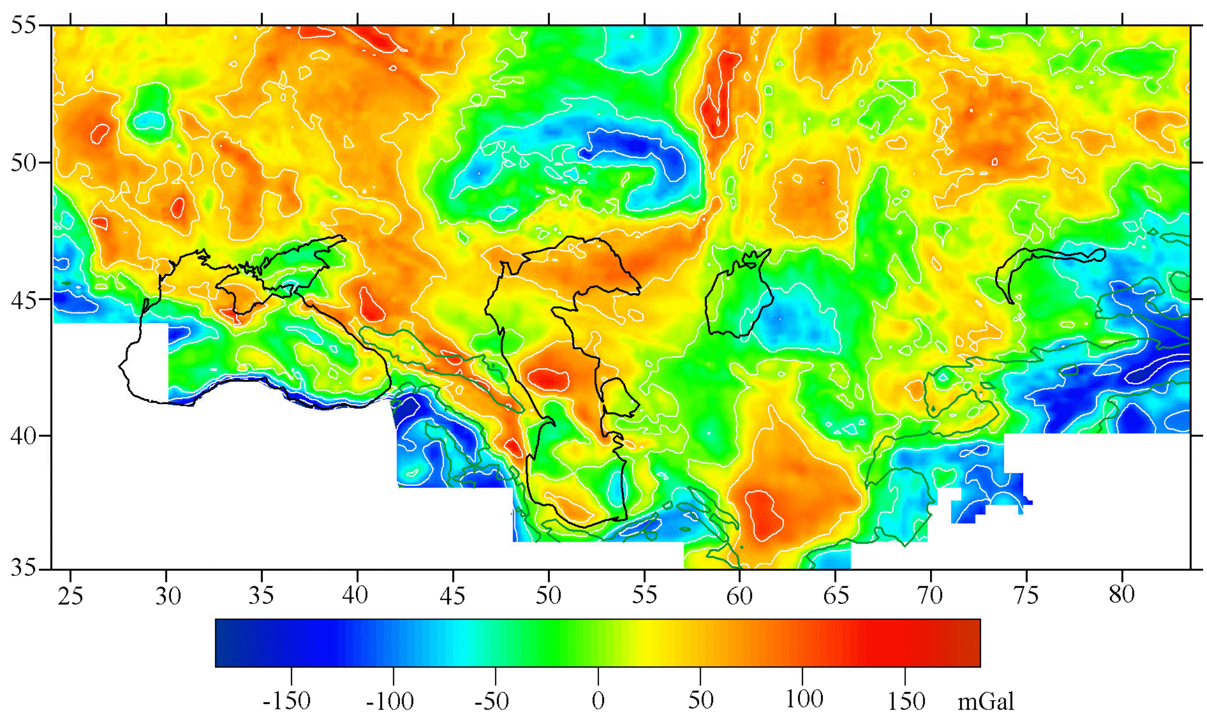

Figure 6. Mantle gravity anomaly map.

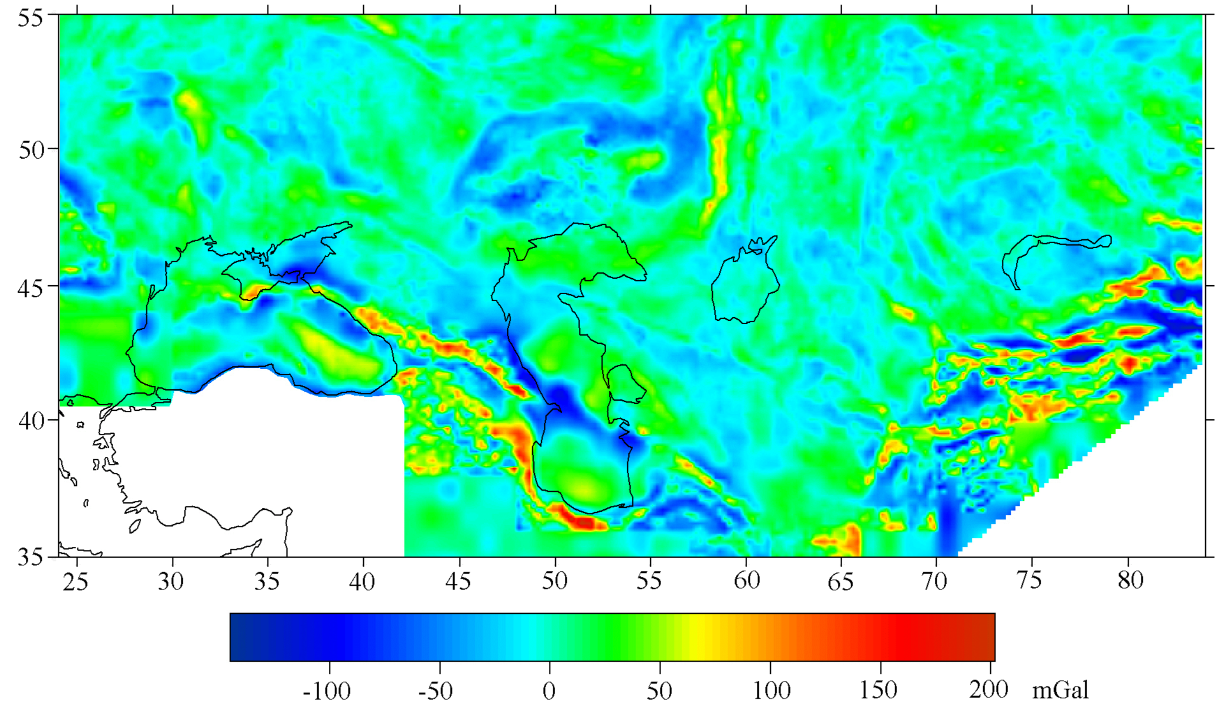

Figure 7. Isostatic gravity anomaly map.

Horizontal gradients of isostatic anomalies and fault-block structure of the lithosphere

Based on isostatic anomalies thus obtained, their horizontal gradients were calculated using routine dependencies (Figure 8). The gradient field has a rather complex pattern. It displays clearly overlapping gradient zones of varying steepness and width, likely portraying the complex and hierarchically organized crustal structure of the region. In order to identify active between-block boundaries, I isolated

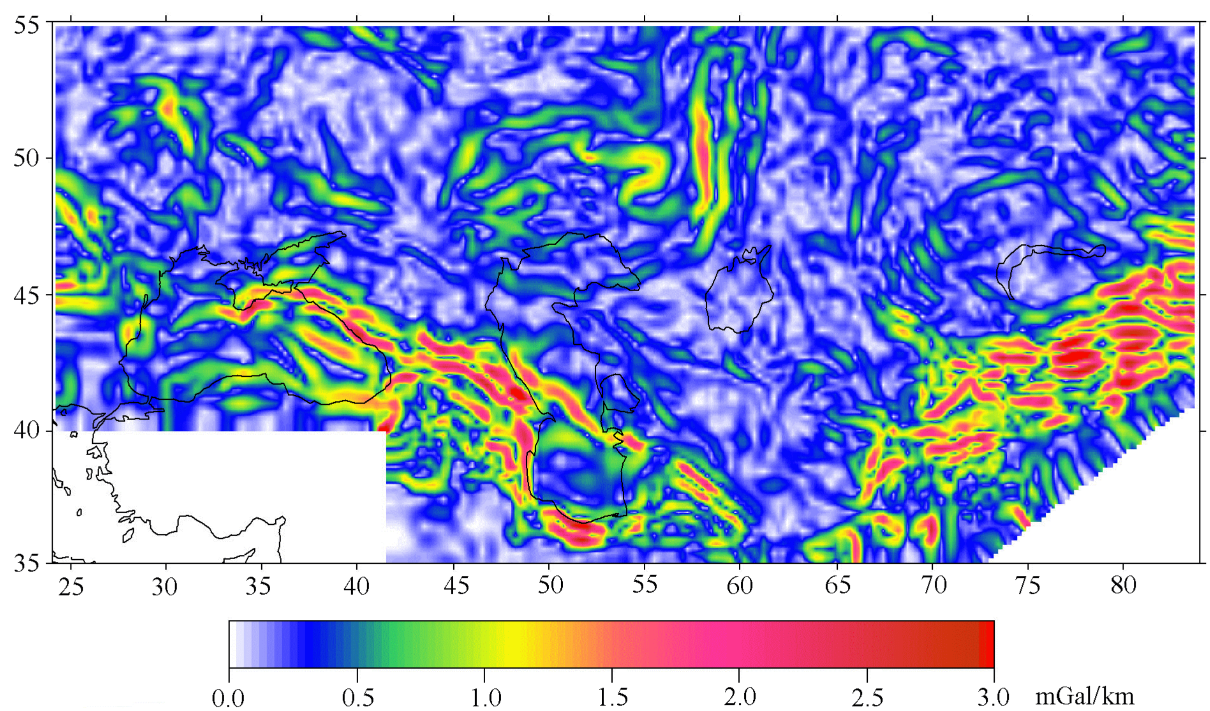

Figure 8. Map showing horizontal gradients of isostatic anomalies.

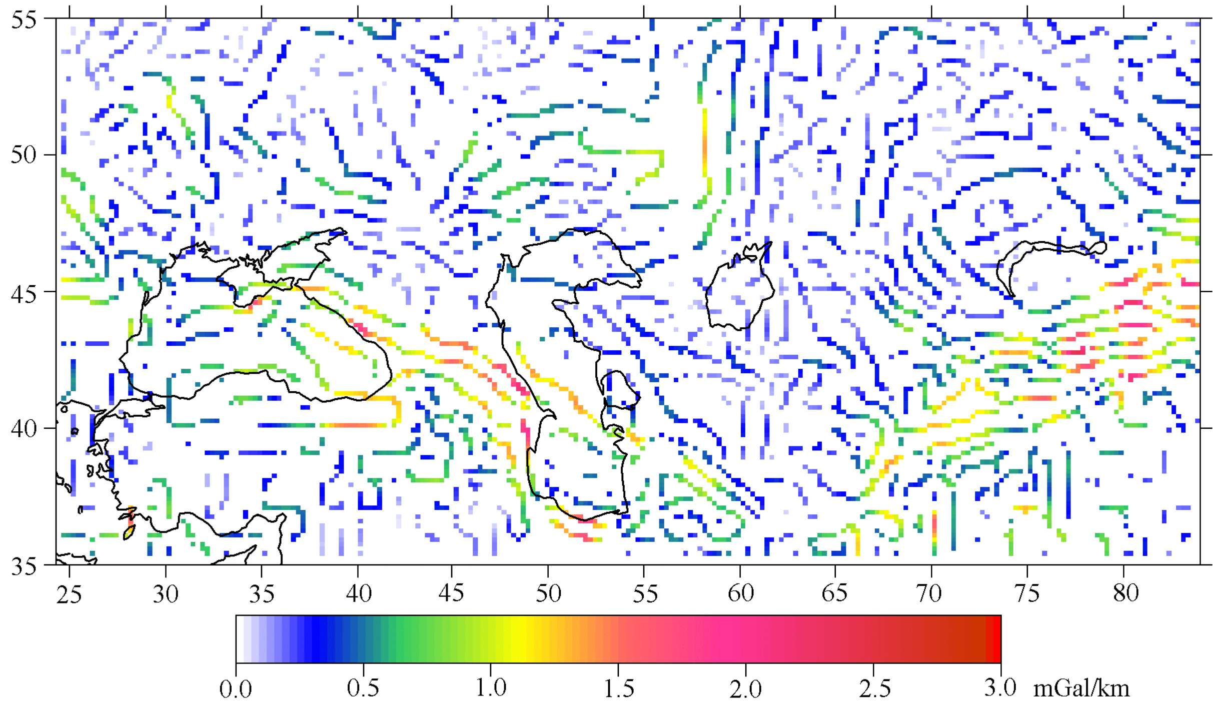

Figure 9. Map showing local maxima of horizontal gradients of isostatic anomalies.

those values of horizontal gradients of isostatic anomalies that are largest relative to their two neighboring ones along at least two of the four possible directions [*Kaban et al.,* 1998]. Distribution of these maxima is shown in Figure 9. Nearly everywhere, the values thus identified merge into large zones, which I take to correspond to block boundaries.

Moduluses of horizontal gradients of isostatic anomalies are as large as 3 mGal/km in the study region. These maxima are recorded in the axial part of the eastern half of the Greater Caucasus and over the southwestern slope of its eastern part. In Tien Shan and Pamir, lineaments are as distinct, albeit much more fragmented. Local second-order positive anomalies of at least 0.6 mGal/km also have an ordered character. Narrow and large zones are delineated in mountain edifices and their adjacent areas alike.

The pattern of gradient zones within the Turan plate and Kopet Dagh is less fragmented than in the western Caspian and neighboring areas of the Caucasus and the Scythian plate. Actually, it exhibits only two boundaries, separating the Kopet Dagh massif from its adjacent areas. Standing out as a white spot in the intricate picture described above is the south Caspian-west Turkmen basin area.

Gradient zones of isostatic anomalies rim chiefly the nearly vertical contacts between rocks with contrasting anomalous densities within the crust. Naturally, most deep faults must produce such contacts. Generally, the plan view location of these zones supports this inference. It is also pretty obvious that, in tectonically complex areas, density contacts can be more distinct due to a wider range of lithologies, displaced by tectonic movements into various depth levels. Therefore, the identified gradient zones depict major tectonically disturbed zones, mostly of fault nature. In terms of their width, these zones most likely correspond to rather wide zones of crustal deformation.

Residual mantle anomalies and isostatic gravity anomalies, obtained in this and previous sections, as well as the identified maxima of horizontal gradients of isostatic anomalies, provide a new basis on which to carry out a comparative analysis of principal types of geostructures within the study area. This problem is handled in the sections that follow.

Lithospheric density inhomogeneities and their tectonic implications

Western and Eastern Caucasus

Along the axis of the Greater Caucasus stretches a distinct zone of positive isostatic anomalies, in places exceeding 100 mGal (Figure 7). In view of the lack of any perceptible sources for these anomalies in the upper crustal portions of the Greater Caucasus, it only remains to assume that this structure is indeed uplifted from its equilibrium position. Several plausible interpretations of this setup exist, but they all call for considerable horizontal compression existing in the region (e.g., [*Kaban and Artemjev,* 1993; *Khain and Koronovsky,* 1997; *Koronovsky,* 1999; *Mikhailov et al.,* 1999]). One possible explanation invokes one or another lithospheric plate underthrusting the Greater Caucasus and thus providing elastic support to part of its load. This hypothesis is best elaborated mathematically and numerically in C. Beaumont's works [*Beaumont et al.,* 1996].

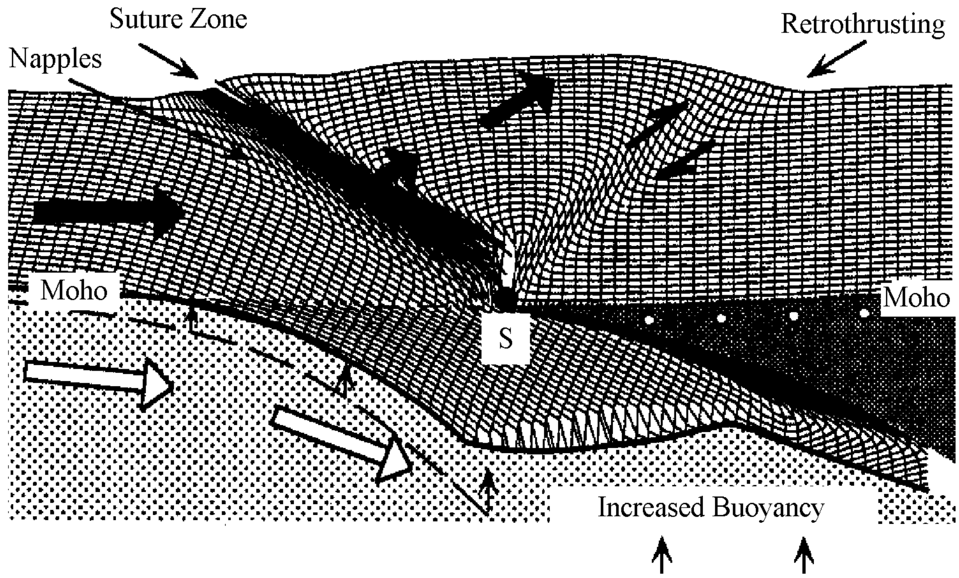

Figure 10. Scheme showing the mechanical model for an intracontinental orogen resulting from plate-to-plate collision [*Beaumont et al.,* 1996]. Curve at the top of the plot depicts the distribution of isostatic gravity anomalies across such an orogen.

Currently, no consensus exists about the likely direction of such underthrusting, because numerical results suggest that the configuration of inclined boundaries, as imaged by seismics, should be roughly the same on both sides of the orogen, irrespective of this direction [*Quinlan et al.,* 1993], although this concept is itself almost commonly accepted. However, as appears from Figure 10, isostatic anomaly configuration will differ fundamentally as a function of the direction. Provided a plate is being thrust under the orogen elastically, its neighboring area should be characterized by a large negative isostatic anomaly, whose width depends on the plate's flexural rigidity. Therefore, analyzing isostatic anomalies on both sides of an orogen helps clarify this issue to some extent.

It turns out that the portion of the Scythian plate adjoining the eastern Caucasus is in fact featured by considerable isostatic lows, which offers a virtually unequivocal answer to the question on the possible direction of the *ongoing* underthrusting: Provided it exists at all, it is directed southward. Note also that the pattern of principal boundaries in the vicinity of the Terek-Caspian trough is also consistent with this model, and the effective thickness of the elastic plate, as obtained through mechanical flexure modeling and by comparing the model with observations, is 17 km [*Kaban and Artemjev,* 1993]. This model is further supported by the fact that, in the upper mantle under the Kura basin, a high density body is detected (Figure 6), likely associated with the lower portion of the Scythian plate sinking beneath the Caucasus.

At the same time, nothing of the kind has been revealed from the western part of the Greater Caucasus or its adjacent structures. The character of isostatic anomalies there fits much better the hypothesis of quasi-plastic deformation and stacking of the crust [*Mikhailov et al.,* 1999]. The reason for this might be that, in the western Caucasus, the lithosphere is considerably hotter and, hence, weaker. In this situation, the high density region in the upper mantle is displaced across the Main Caucasus Range, toward the Indol-Kuban basin.

The distribution pattern of the maxima of horizontal gradients of isostatic anomalies is in complete agreement with the above inferences (Figure 9). Values as high as 2.5 mGal/km separate the Dagestan block from the Terek-Caspian trough. This gradient zone stretches EW from the Caspian Sea to long. 45°E, almost coinciding with northern foothills of the eastern Caucasus. Further west, the northern boundary of the Caucasus is traceable by a strip of considerably lower gradients, displaced from the foothills southward, toward the front ranges.

The Dagestan block is delineated in the north by a strip of high-gradient values (Figure 9). Near the Caspian coast, this strip swings southeast and extends coastwise at lower values. West of Limestone Dagestan, the gradient zone ends, and further west still, two roughly E-W trending strips emerge, one of which, that with lower gradients, stretches along the northern margin of the Laba-Malka homocline, while the other, southern, coincides with the northern slope of the Frontal Ranges zone. Curiously, the interior of the homocline exhibits a patchy system of gradient zones, apparently suggestive of heavy fragmentation of the earth's crust here.

A distinct zone of disturbances of the linked lines of maximum gradients marks the boundary between the western and eastern Caucasus. This zone coincides with the high seismicity zone [*Ulomov,* 1998; *Ulomov et al.,* 1999]. In addition, it was identified earlier using geologic data [*Koronovsky,* 1999].

Therefore, comparison of the above gravity field conversions between the western and eastern portions of the Greater Caucasus leads to the incisive conclusion that their present-day tectonic settings are considerably dissimilar.

Kopet Dagh

The Kopet Dagh and the Kopet Dagh foredeep display a distinct linear dipole structure nearly 700 km long, reflected in all the fields. Within the Kopet Dagh, an isostatic high of up to 50–70 mGal is identified, while the Kopet Dagh foredeep exhibits an isostatic low roughly as large in modulus. The Kopet Dagh foredeep ranges in width from 30–40 km in the west to 100 km in the east. Its outer slope is wide and gentle, and inner, narrow and steep. The foredeep occurs in a fault junction, along the system of normal and thrust faults of the southern Turkmen marginal basin, with the Kopet Dagh. Sedimentary fill of the foredeep includes carbonate and terrigenous strata of Meso-Cenozoic age as thick as 10 to 14 km. The residual anomalous field suggests that, beneath the Kopet Dagh Range, an anomalously low-density (ca. -50 kg/m^3) mantle material occurs. The mantle density under the Kopet Dagh foredeep does not depart perceptibly from normal values [*Kaban et al.,* 1998].

Such a pattern of the anomalous gravity field and near-surface structural features suggests even more strongly than for the eastern Caucasus that the quasi-equilibrium state of the lithospheric plates in this region is ensured not following the local isostasy principles, but mechanically, i.e., by lithospheric stresses. This hypothesis was elaborated in a series of papers [*Artemjev and Kaban,* 1994; *Kaban et al.,* 1998]. Mechanical modeling shows that the shape of the boundary of the Turan plate might result from the plate's elastic flexure due to forces at work in its contact zone with the Kopet Dagh. The effective thickness of the elastic plate is 25±5 km. Several mechanisms of their interaction are conceivable (Figure 11).

1. Hard plate-to-plate contact, resulting in a gradual destruction of the Turan plate as the two plates are converging, being driven by horizontal forces directed from south to north, with ensuing "squeezing out" of the Kopet Dagh. In such an event, the Kopet Dagh load cannot ensure the necessary degree of deformation of the Turan plate. Assumedly, an additional force, applied to the Turan plate's margin, results from the horizontal force (T), produced by the Kopet Dagh colliding with the Turan plate (Figure 11).

2. Partial underthrusting of the Turan plate under the Kopet Dagh. This would involve the lithospheric mantle and the densest portion of solid crust sinking gradually southward, while the middle and upper lithospheric sections are being detached, likely at the main fault, to form the Kopet Dagh Range. In such a situation, the Moho under the Kopet Dagh, positioned not reliably enough based on sporadic seismologic data, is in fact a gently inclined, nearly horizontal boundary, separating the overlapping plates, while the low density mantle under the Kopet Dagh is in reality the reworked lower portion of solid crust of the Turan plate. The ambiguity of the solution to the inverse gravity problem makes this inference admissible, because the depth distribution of density anomalies, resulting in the mantle anomaly, is not determined consistently. Importantly, in such an event the load from the Kopet Dagh accounts for the observable deformation of the Turan plate in full measure, thus making the introduction of any additional forces redundant.

3. Analysis of additional information is alone helpful in choosing between one or another model. Figure 12 shows the section view of earthquake foci positions and the distribution of total seismic energy along the profile. The figure demonstrates a sharp peak in released seismic energy corresponding to the northern slope of the Kopet Dagh, which further supports Model 1, "hard" plate-to-plate interaction. The high seismicity region should, thus, be associated with the zone where the destruction of the Turan plate is occurring. Besides, the sinking of the relatively light-weight continental crust in the upper mantle is problematic.

The totality of evidence thus suggests definitely that Model 2 for plate-to-plate interaction in its pure form is spurious. In this situation, however, a combination of the two models is possible. It can be hypothesized that the lithospheric mantle of the Turan plate, possibly along with a portion of its lower crust, is sinking in the mantle beneath the Kopet Dagh, while the rest of the crust is being detached from its underlying lithosphere and destroyed. The locus of break-off and destruction corresponds to the location of the seismic energy maximum. This inference is further supported by the fact that the sinking portion of the plate is lacking earthquake foci, which points to the absence of essential stresses in it.

Black Sea basins

Our study lends no support to the repeatedly hypothesized existence of a considerably low-density upper mantle region under the Black Sea (i.e., [*The Gravity Model...,* 1979]. It turns out that the deepest basement sags (Figure 3) and Moho uplifts (Figure 5) compensate for each other fully, resulting in close-to-zero mantle anomalies (Figure 6). The only exception is the westernmost portion of the Black Sea, where one observes the margin of a negative regional mantle anomaly extending further west. Isostatic anomalies are very slightly differentiated here as well, except in the zone immediately next to the western part of the Greater Caucasus, where isostatic anomalies exhibit extremely high gradients (Figure 8). Generally speaking, the extension of the Greater Caucasus zones is traceable by isostatic anomalies across the eastern part of the Black Sea. All the above portrays the Black Sea as a smooth and currently passive tectonic feature, which, considering the thinness of its solid crust [*Volvovsky and Volvovsky,* 1979] and its high crustal seismic velocities (Vp = 7 km/s or more), can be ranked with quasi-oceanic structures.

Caspian Sea

Unlike the Black Sea, the Caspian brings together utterly contrasting structures, which deserve special consideration.

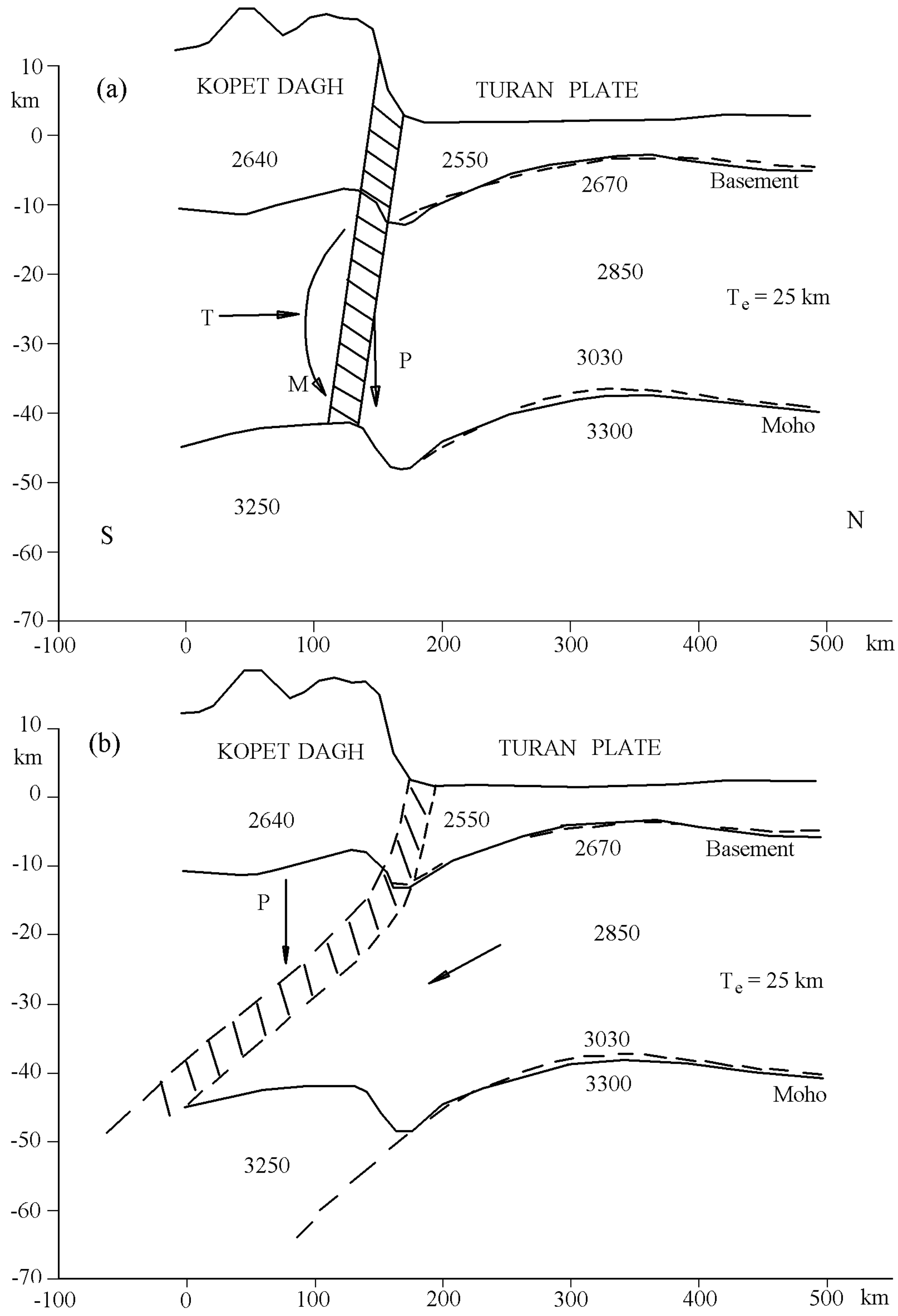

Figure 11. Mechanical models of the Turan plate-Kopet Dagh interaction. (A) The southern boundary of the Turan plate is under the northern slope of the Kopet Dagh and corresponds to the Kopet Dagh fault (stippled area). To deform the Turan plate, a horizontal pressure and a bending moment are required. The deformation of the plate and its effective elastic thickness $T_e = 25 \pm 5$ km have been estimated from the seismic cross-section. Densities inside the crust and under the Moho, as determined from the model. (B) The Turan plate-Kopet Dagh interaction in the framework of the subduction model.

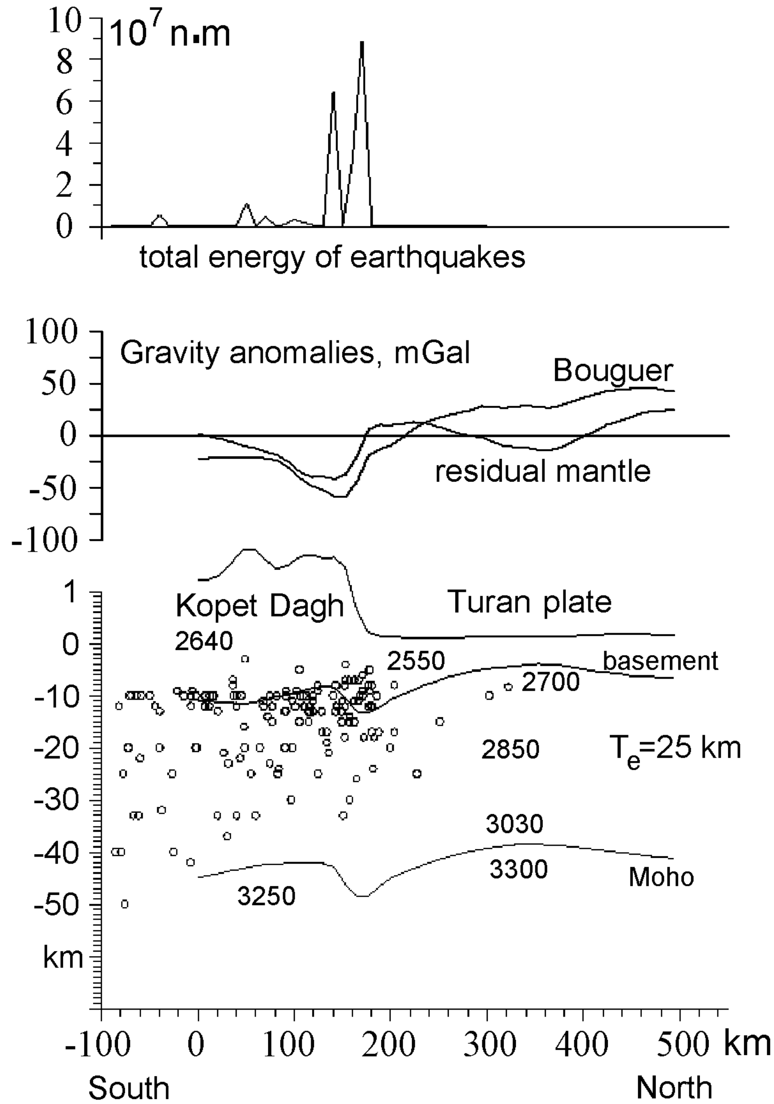

Figure 12. Geophysical cross-section along the Kopet Dagh-Aral Sea DSS profile [*Ryaboy,* 1968]. 1 – seismic energy release along the profile, 2 – Bouguer and subcrustal gravity anomalies (in mGal), 3 – seismic cross-section and earthquake hypocenters.

Central Caspian Sea and Karabogaz arch

The Karabogaz arch emerged above the eastern end of a major Paleozoic median mass, traceable across the central Caspian basin as far as eastern Cis-Caucasia. The median mass is a Precambrian or Early Paleozoic cratonic area, rimmed by mobile zones of Hercynian orogeny. The Karabogaz arch is a major gentle uplift some 100 km by 200 km in size along basement surface. Basement of the Karabogaz arch is composed of highly deformed and metamorphosed sedimentary rocks, pierced by intrusive and extrusive bodies. The arch exhibits an isostatic high of up to +70 mGal (Figure 7). This means that the isostatic model used to calculate these anomalies is at odds with reality. Furthermore, it turns out that an isostatically balanced lithospheric density model accommodating those considerably lower isostatic anomalies for the region in point cannot be proposed in principle. Isostatic highs can be reduced somewhat by placing negative compensating masses at a depth as great as 200 km. This really allows reducing the highs by ca. 10 mGal [*Kaban et al.,* 1998], but upsets considerably the isostatic anomalous field in adjacent areas.

To unravel the nature of these anomalies, it is critical to note that the feature that neighbors on the Karabogaz arch in the southwest exhibits diametrically opposing characteristics. The northwest part of the South Caspian basin displays one of the largest isostatic lows on the entire former USSR territory, up to −120 mGal (Figure 7). This low cannot be attributed to anomalous masses of sedimentary cover. Numerical calculations have shown that even placing compensating masses at great depths, 200 km or deeper, cannot reduce the observed isostatic low considerably [*Kaban et al.,* 1998]. At the same time, residual anomalies in this locality are ca. +100 mGal, suggesting a high density body in the mantle here, which might be the likely cause of the lithospheric block being depressed from its equilibrium position.

It thus can be concluded that the Karabogaz arch and the northwest part of the South Caspian basin are really characterized by an extraordinary departure from isostatic equilibrium. Note also that the surface heat flow within the Karabogaz arch is ca. 75 mW/m^2 [*Smirnov,* 1980], a value notably higher than normal. In the vicinity of the Apsheron sill and in the northwestern South Caspian basin, all the lithospheric geophysical characteristics are in complete contrast to the above. Assessments of tectonic stresses from this area show the dominance of a roughly horizontal compressional component, normal to zones of important vertical tectonic deformations [*Gushtenko et al.,* 1993]. These deformations are heaviest in the zone separating the Karabogaz arch from the South Caspian basin. The total magnitude of Neogene-Quaternary differential vertical movements, as assessed from these structures, is ca. 10 km [*Gorshkov,* 1987]. In addition, this zone is highly seismic, to mention but the M = 8.2 Krasnovodsk earthquake. In its turn, the Talysh folded area, adjacent to the southern Caspian on the southwest, exhibits an isostatic high as large as +150 mGal, which renders it somewhat similar to the Karabogaz arch.

The results obtained suggest that the positive isostatic anomalies and high heat flow values within the Karabogaz arch and, possibly, in the Talysh area, as well as the contrasting properties of the lithospheric features southwest of the arch, are due to mantle movements that ensure dynamic equilibrium of the lithosphere there. An upwelling flow must be located under the arch, and a downwelling flow, under the Apsheron sill and the southwestern part of the South Caspian basin. It remains unclear whether these flows are interrelated, i.e., whether they constitute a single small scale convective cell in the upper mantle or not. If this is the case, then the "negative" structure in the vicinity of the Apsheron sill and northern part of the South Caspian brings together upwelling mantle flows from its two neighboring areas, which would explain its far more conspicuous, in terms of absolute values, characteristics, as compared to its neighboring "positive" structures.

South Caspian

The South Caspian, except for its northernmost part, described in the previous section, exhibits a smooth isostatic pattern (Figure 7). As mentioned above, zones of maximum gradients sort of bypass it in the north and south (Figure 9). This suggests that the lithosphere in this part of the Caspian Sea is considerably weakened, i.e., it is incapable of maintaining elastic stress for a longer time.

The eastern part of the South Caspian, also known as the western Turkmen basin, unlike the central zone of the South Caspian, exhibits negative mantle anomalies as large as −75 mGal. These anomalies can only be attributed to a reduced density of the subcrustal layer [*Kaban et al.,* 1998]. The thickness of solid crust within this structure is a mere of 5 km [*Kunin et al.,* 1992]. This area is also lacking in "granite" Layer 1 of the typical continental crust, characterized by P-wave velocities of ca. 6 km/s. Other distinctive features of the South Caspian are extensive diapirism and mud volcanism. All these parameters, just as the crustal structure comprising extremely thick sediments and thin high-velocity solid crust, render the South Caspian a likely candidate for a marginal basin [*Kaban,* 2001]. Apparently, the South Caspian zone once represented a sort of "pocket" within the relatively rigid plate, which enabled it to survive the closure of the Tethys and to turn into a huge depository of sediments, supplied from its neighboring orogens.

Northern Caspian

This feature exhibits near-to-zero isostatic anomalies, suggestive of the lack of tectonic processes underway there. The only exception is the zone adjacent to the Terek-Caspian trough. Essential tectonic fragmentation is recorded in its adjacent areas of the Scythian plate and within the Caspian Sea alike. The most remarkable feature is a strip of rather steep gradients stretching seaward in a northeasterly direction from Makhachkala, i.e., from the northeasternmost part of the Dagestan wedge.

The field of residual mantle anomalies clearly displays positive features that can be identified as the extension of the Magnitogorsk zone of the Central Urals.

Tien Shan

This feature displays extremely large, up to −150 mGal, residual gravity anomalies, most of them being induced by anomalous upper mantle. This lends further support to the inference, already proposed in [*Lopatina and Ryaboy,* 1972], that the Tien Shan uplift is compensated largely due to reduced mantle density, rather than crustal thickening. This mantle root is traceable as far as the Aral Sea. According to the compensation model constructed, mantle density beneath the Tien Shan must be ca. 0.1 g/cm^3 lower than normal [*Artemjev and Golland,* 1983; *Artemjev and Kaban,* 1994]. By and large, this value is consistent with upper mantle velocity anomalies delineated by seismic data [*Kosarev et al.,* 1993; *Roecker et al.,* 1992; *Vinnik and Lukk,* 1976].

This supports the conclusion, deduced from seismic surveys [*Kosarev et al.,* 1993], that mantle characteristics are dissimilar beneath the western and eastern Tien Shan, on the two sides of the Talas-Fergana fault. The western Tien Shan exhibits increased values of both upper-mantle seismic velocities and mantle gravity anomalies. However, as regards gravity anomalies, this conclusion requires further testing, because primary information on crustal structure here is not reliable enough as yet.

Isostatic anomalies are rather large within Tien Shan, but their variations are of an extremely local character (Figure 7), which renders them attributable to overlooked density variations in the upper crustal portion, mainly, in sediments. Conceivably, these linear anomalies resulted from horizontal compression of a pre-heated structure or from syncompressional heating of the structure. In this respect, Tien Shan strongly resembles the Lesser Caucasus area, although their sources of abnormally hot mantle may be different.

Lesser Caucasus

The totality of gravity modeling results points to its similarity to Tien Shan (Figures 6–8). The upper mantle displays the same degree of density reduction, and isostatic anomalies have a local character, despite their large values there. Hence, despite the huge genetic difference between these structures, their present-day geodynamic characteristics appear to be similar. The density model obtained for the Lesser Caucasus fits in well with the scheme according to which this structure emerged after the closure of the Tethys, on the site of a former marginal sea [*Zonenshain and Savostin,* 1981]. As discussed above, the South Caspian area for a variety of reasons escaped such destiny.

Eastern Turkmen syneclise

The eastern Turkmen syneclise, also known as the Murgab basin, displays Mesozoic and Cenozoic strata as thick as 15 km. In keeping with the model obtained, the anomalous density of the subcrustal lithospheric layer is ca. +40 kg/m^3 here [*Kaban et al.,* 1998]. Isostatic anomalies are close to zero within this region, which points to its isostatic balance being close to equilibrium. Note that raw data providing the basis for the model obtained for the Murgab basin area are not reliable enough. This refers primarily to crustal thickness and sediment density, which was calculated using the same dependencies as for the Kopet Dagh foredeep. Therefore, conclusions obtained for this structure should be viewed as preliminary. In particular, a certain increase in the average sediment density would help avoid increasing the density of the subcrustal layer, because the nature of this excess density is not quite clear. It can only be surmised that in Mesozoic time this area was affected by downwelling mantle flows, likely associated with upwelling flows that may have existed simultaneously in the vicinity of the central Karakum arch. Sedimentation and ensuing cooling of the mantle material resulted in isostatically compensated sagging of ca. 12 km. Currently, the structure thus formed is stable and sort of "frozen" into its surrounding lithosphere.

Conclusions

Tectonically, the study area is utterly complex. In terms of intensity and range of processes occurring here, it is virtually unparalleled throughout northern Eurasia. The Alpine-Mediterranean foldbelt, which emerged after the closure of the Tethys, occupies a central position in this area. The overall geodynamic setup here is determined by compression directed roughly N-S and related to the ongoing convergence of the African-Arabian and Eurasian plates. Nevertheless, it turns out that lithospheric structure within this belt varies broadly. This is especially clear from the patterns of mantle and isostatic gravity anomalies (Figures 6 and 7, respectively). The general setup is further complicated, particularly in the southeastern part of the study region, by strong pressure from the Indostan plate. It is absolutely clear, however, that a roughly N-S directed compression cannot alone account for the entire range of recent structures and processes encountered in the study region.

Mantle gravity anomalies (Figure 6) are induced by density anomalies in the upper mantle, due to its thermal regime and composition alike. These density variations bear notably on the character of plate-to-plate interaction, resulting in the broad spectrum of tectonic processes in the study region. If one considers the region as a whole, the zone of increased values of mantle anomalies, suggestive of an increased density of the subcrustal layer, is located north of the contact zone between the plates. Positive anomalies are related chiefly to structures of the Eastern European craton, including the southern terminus of the Urals and, partially, the Turan plate. The density of the subcrustal layer may be increased here some 0.05 g/cm^3 as compared to the regional average value. The lowest values of mantle anomalies are characteristic of the Lesser Caucasus with its adjacent Pontus block and of Tien Shan. These lows may attain values of -175 mGal, which might imply a density deficit of -0.06 to -0.08 g/cm^3. The latter values depend on how deep this density deficit reaches. This issue cannot be resolved by means of gravity methods alone.

In addition, the study area exhibits extraordinary values of isostatic anomalies. Despite the fact that the use of real data on crustal structure enabled us to considerably reduce their magnitude over certain regions, this magnitude remains quite significant, as large as 150 mGal. We have much better reasons to view the anomalies calculated in this work, as compared to those obtained in previous works, as isostatic, i.e., indicative of departures from isostatic equilibrium, rather than departures of real crustal structure from oversimplified schemes such as those of Airy and Pratt.

The general patterns of isostatic anomalies (Figure 7) and their horizontal gradients (Figures 8, 9) are in keeping with the plate-to-plate interaction scheme. The gradient zones identified here reflect major tectonic zones. Figure 9 displays, first of all, extremely high gradient zones, corresponding to the Alpine-Mediterranean belt and the Pamir-Tien Shan area. These zones form an angle with its apex near the southeast terminus of the Kopet Dagh. Besides, in terms of their location, they correspond to the zone where upper mantle characteristics undergo a change, which suggests these zones might be global boundaries separating sharply dissimilar lithospheric blocks. Let us detail the different types of orogens existing in the study area. Based on their integrated parameters, these orogens can be classed into two groups. The Greater Caucasus and Kopet Dagh rank with purely collisional orogens, resulting from the collision and subsequent interaction of lithospheric plates. To narrow our discussion to the gravity field alone, these orogens are characterized by significant isostatic anomalies, whereas mantle anomalies are not pronounced here. Nevertheless, even within this type essential distinctions are detected. The eastern Caucasus and its adjacent Scythian plate exhibit comparatively wide zones of isostatic anomalies, suggestive of true departures from isostatic equilibrium, due to, e.g., partial underthrusting of one plate under the other. The same can be deduced from the configuration of the base of the Scythian plate, whose shape is consistent with the elastic flexure model. Within the western Caucasus, isostatic anomalies have a much more local character and might be due to density inhomogeneities that cluster in the upper crustal section and that remained unaccounted for in the original model. Here, it is more reasonable to infer the presence of quasi-plastic crustal deformation, possibly because the lithosphere is hotter and, consequently, weaker mechanically. The central Caucasus, separating the western and eastern parts of the Greater Caucasus, also differs from these parts in terms of the whole spectrum of geologic and geophysical data. The maps showing isostatic anomalies and their gradients (Figures 7–9) portray clearly a roughly N-S trending boundary zone, with the central Caucasus segment being its part.

The Kopet Dagh has more features in common with the eastern Caucasus, i.e., it results from a "hard" contact between lithospheric plates, although, apparently, it bears evidence of an impact from the Indostan plate, which leads to a considerable slip of the Kopet Dagh relative to the Turan plate with the resultant smaller values of isostatic anomalies.

The Lesser Caucasus and, especially, Tien Shan differ dramatically from the orogens just described in that they exhibit a sharply reduced density of their subcrustal layer, due primarily to its higher temperature. Conceivably, the formation of these structures was controlled by two factors, (i) a roughly N-S compression and (ii) independent crustal deformation caused by the emplacement of anomalous mantle material. This conclusion is corroborated by geologic evidence [*Chediya,* 2000]. The nature of the anomalous mantle may vary. As regards Tien Shan, it can be hypothesized that this feature was initiated as an intracontinental rift, which then suffered compression as the Eurasian and Indostan plates collided.

The Black Sea basins and, especially, the southern part of the South Caspian basin, exhibit a smooth field of isostatic anomalies, even though these structures occur virtually along the line of interaction of the lithospheric plates. This suggests that the lithosphere in these areas has a reduced strength and is incapable of maintaining considerable stresses. While the Tethys still existed, these structures were marginal seas, which would account for their lithospheric weakness, inherited from that time. The present-day marine basins might represent irregularities of sorts within the relatively rigid plate, which enabled them to survive the closure of the Tethys and to turn into a huge depository of sediments, washed off the neighboring orogens.

An utterly complex geodynamic setup exists across the vast area that includes the Karabogaz arch and the Apsheron sill along with the northern part of the South Caspian. Results obtained in this work suggest that the lithosphere in this part of the Caspian Sea is depresses from its equilibrium position. The uniqueness of this structure is expressed even in Bouguer anomalies, whose magnitude here is equal to that in the Greater Caucasus area (up to −200 mGal), while its topographic relief is opposite in sign. The attempts to construct an isostatic compensation model that would be anywhere near realistic and permit a perceptible reduction in isostatic anomalies in this area fared poorly. For the Karabogaz arch and a part of the Talysh folded area, quite the reverse result was obtained. Hence, we are dealing here with a well-developed dipole structure, lacking visible links with the general roughly N-S compression trend. Positive isostatic anomalies and high heat flow values within the Karabogaz arch (and, possibly, the Talysh area), just as the reverse lithospheric characteristics in the central Caspian area, can be explained by mantle movements ensuring dynamic equilibrium of the lithosphere. An upwelling mantle flow must be located under the arch, and a downwelling flow, under the central Caspian and southwest part of the South Caspian basin. It is not yet clear whether these flows are interrelated, i.e., whether they constitute a convective cell in the upper mantle.

Acknowledgments. This work was supported by the Russian Foundation for Basic Research (project no. 01-05-64381).

References

Artemyev, M. E., and V. E. Golland, Isostatic compensation of Tien Shan, Choice of compensation model, *Phys. Solid Earth, 19,* (1), 30–37, 1983.

Artemjev, M. E., and M. K. Kaban, Density inhomogeneities, isostasy and flexural rigidity of the lithosphere in the Transcaspian region, *Tectonophysics, 240,* 281–297, 1994.

Artemyev, M. E., V. E. Golland, and G. A. Niauri, New data on the isostasy of the Caucasus, *Physics of the Solid Earth, 21,* (2), 85–93, 1985.

Artemyev, M. E., A. P. Belov, M. K. Kaban, and A. I. Karaev, Isostasy of the lithosphere of Turkmenia, *Geotectonics, 26,* (1), 48–58, 1992.

Artemjev, M. E., M. K. Kaban, V. A. Kucherinenko, G. V. Demjanov, and V. A. Taranov, Subcrustal density inhomogeneities of Northern Eurasia as derived from the gravity data and isostatic models of the lithosphere, *Tectonophysics, 240,* 249–280, 1994.

Beaumont, C., S. Ellis, J. Hamilton, and P. Fullsack, Mechanical model for subduction-collision tectonics of Alpine-type compressional orogens, *Geology, 24,* (8), 675–678, 1996.

Chedia, O. K., Orogenic areas, Central Asia, in: Grachev A.F., Editor, *Neotectonic, Geodynamics and Seismicity of Northern Asia* (in Russian), Probel Publ., Moscow, pp. 80–92, 2000.

Gordin, V. M., and M. K. Kaban, Isostatic residual and decompensated gravity anomalies and gravity data on the upper crust heterogeneities (Central and southern parts of the East-European platform and the Caucasus), Final report, Mobil Oil and Zonenshain Centre for Russian Geology and Tectonic, Univ. of Texas, Arlington, 1995.

Gorshkov, G. P.,*Seismotectonics of the Kopet-Dag (in Russian)*, 52 p., Nauka, Moscow, 1987.

Gushtenko, O. I., A. V. Mikhailova, A. O. Mostrjukov, and V. A. Petrov, The regional stress-monitoring and the mechanism of deforming Caucasus-Iranic seismoactive zone, in: *Seventh meeting of the European Union of Geosciences,* Terra Abstracts. 5, Suppl. 1, p. 218, 1993.

Kaban M. K., A gravity model of the North Eurasia crust and upper mantle: 1. Mantle and isostatic residual gravity anomalies, *Russian Journal of Earth Sciences, 3,* (2), 125–144, 2001.

Kaban, M. K., and M. E. Artemjev, The Density Lithosphere structure of the Eastern Europe and Its Relation to Tectonics, *Terra nova, Abstr. suppl. (EUG VII, Strassburg), 5,* No. 1, p. 54, 1993.

Kaban, M. K., and P. Schwintzer, Oceanic upper mantle structure from experimental scaling of Vs and density at different depths, *Geoph. J. Int., 147,* 199–214, 2001.

Kaban, M. K, M. E. Artemjev, A. I. Karaev, and A. P. Belov, The deep structure and geodynamics of the tectonic features in Turkmenistan and adjacent areas; gravity evidence, *Geotectonics, 32,* (4), 323–332, 1998.

Khain, V. E., and N. V. Koronovsky, Caucasus, in: *Encyclopedia of European and Asian regional geology,* Collection: Encyclopedia of Earth sciences series, Fairbridge-Rhodes-W (editor), 127–136, 1997.

Koronovsky, N., Collision processes in Caucasus; physical modeling, in: European Union of Geosciences conference abstracts, *J. of Conf. Abstr., 4,* (1), 72–73, 1999.

Kosarev, G. L., N. V. Petersen, L. P. Vinnik, and S. W. Roecker, Receiver functions for the Tien Shan analog broadband network: contrasts in the evolution of structures across the Talasso-Fergana Fault, *J. Geoph. Res., 98,* 4437–4448, 1993.

Kunin, N. Ya., E. R. Sheih-Zade, and G. I. Semenova, *Structure of the Eurasian lithosphere* (in Russian), 266 p., Mezhduvedomstvennii Geofiz. Komitet Rossiiskoi Akademii Nauk, Moscow, 1992.

Lopatina, N. P., and V. Z. Ryaboy, Velocity and density inhomogeneities in the upper mantle of the USSR, *Transactions (Doklady) of the U.S.S.R. Academy of Sciences, 207,* (1–6), 9–12, 1974.

Mikhailov, V. O., E. P. Timoshkina, and P. Polino, Foredeep basins; the main features and model of formation, *Tectonophysics, 307,* 345–359, 1999.

Quinlan, G., C. Beaumont, and J. Hall, Tectonic model for crustal seismic reflectivity patterns in compressional orogens, *Geology, 21,* 663–666, 1993.

Roecker, S. W., T. M. Sabitova, R. Mamatkanova, L. Munirova, L. P. Vinnik, Y. A. Burmakov, and M. I. Golvanov, Investigation of the seismicity, structure, and tectonics of the western and central Tien Shan through the analysis of P and S wave arrival time data, *Eos, Transactions, AGU, 73,* (14), supplement, p. 212, 1992.

Roecker, S. W., T. M. Sabitova, L. P. Vinnik, Y. A. Burmakov, M. I. Golvanov, P. Mamatkanova, and L. Munirova, *J. Geoph. Res., 98,* 15,779–15,795, 1993.

Ryaboy, V. Z., Structure of the Earth's crust and upper mantle in the central regions of Turkmenia according to deep seismic sounding data (DSS), in: *European Seismological Commission,* 8th Assembly, Proc. Akad. Kiado, 216–221, 1968.

Smirnov, Ya. B., *Heat flow and abyssal temperatures maps of the USSR territory. Scale 1 : 1000 000),* Glavnoye Upravlenie Geodezii i Kartografii pri Sovete Ministrov SSSR, Moscow, 1980.

The Gravity Model of the Crust and Upper Mantle, Chekunov, A. V., Ed., (in Russian), Naukova Dumka, Kiev, 1979.

Ulomov, V. I., Focal zones of earthquakes modeled in terms of the lattice regularization, *Physics of the Solid Earth, 34,* (9), 717–733, 1998.

Ulomov, V. I., T. P. Polyakova, and N. S. Medvedeva, Seismogeodynamics of the Caspian Sea region, *Physics of the Solid Earth, 35,* (12), 1036–1042, 1999.

Vinnik L. P., and A. A. Lukk, Horizontal inhomogeneities of the upper mantle in Central Asian regions of platform activation, *Physics of the Solid Earth, 11,* (7), 411–418, 1976.

Volvovskii, I. S., and B. S. Volvovskii, *Crustal Sections in the USSR from Deep Seismic Soundings* (in Russian), Sovetskoe Radio, Moscow, 1975.

Zonenshain, L. P., and L. A. Savostin, Cenozoic geodynamics of the Caucasus and adjacent area, *Eos, Trans., AGU, 62,* (17), 221, 1981.

(Received February 8, 2002)