Mathematical Geology, Vol. 25, No. 7, 1993

A Method to Solve the Paleotectonic Analysis Problem[1]

Valentine O. Mikhailov[2]

The method to determine the rates of tectonic movements is based on the use of dynamic models of sedimentary basins. A standard dataset should be provided as input information: the present-day position of sedimentary layer interfaces (chronostratigraphic boundaries), land surface and basement, the layer ages, and the uncertainty limits within which the depth of sedimentation of each layer may have differed. In terms of dynamic models, the paleotectonic analysis problem is reduced to the determination of such tectonic rates that, at prescribed reference times, the model surface topography within the assumed limits would be constrained. At the final moment, the interfaces would be brought into agreement with the contemporary geologic cross-section. The analysis the problem of tectonic rates determination has shown that it has no unique solution. One of the ways to obtain the unique solution is to seek it within a prescribed class of functions, for example, the Fourier series. This method differs from the paleotectonic analysis methodology in that it treats the tectonic rates of motion as functions of time and spatial variables. Under certain conditions, it proves feasible to reconstruct the rates of tectonic movements not only within the time intervals represented in the deposited strata, but within periods of erosion as well. It also is possible to take into account the deformation-induced changes in thickness of the layers. The method's application is illustrated with an example of the Terek-Caspian Trough. As follows from the computation, the tectonic movements since the Middle Jurassic may be presented as a sum of two components: an overall slowing-down subsidence whose rate is proportional to the square root of the age, and local movements which follow a regular oscillatory time pattern with a period of 60–70 MY. The character of the local movements is such that the profile appears to break into a northern and southern segment. When one was being uplifted, the other segment was sinking, and vice versa. *These two segments are separated by a deep-seated fault. This may have been a result of an external compression on the trough.*

KEY WORDS: tectonic-movement rate, deterministic model, sedimentary basins, paleotectonic analysis, Terek-Caspian Trough.

INTRODUCTION

To solve many important problems requiring, for instance, lithospheric and mantle phenomena and the way they interact to bring into existence various

[1] Received 26 November 1992; accepted 19 April 1993.

[2] Institute of Physics of the Earth, Russian Academy of Sciences, B. Gruzinskaya 10, Moscow, Russia.

0882-8121/93/1000-0949$07.00/1

structures, or the behavior of the lithospheric layers under different tectonic forces, it is essential to know the rates of paleotectonic movements. Most methods to determine these rates have their origin in the one named for the thickness and facies change analysis, or paleotectonic analysis, originally proposed for the analysis of the purely vertical tectonic movements (Beloussov, 1938). It uses the data on the thickness, age, and depth of formation (facies composition) of the sedimentary strata. According to Beloussov (1980) the thickness of any sedimentary layer gives information about the total vertical displacement (but not about any short-term variations) for the time between this and the next layer's formation. The thickness of the sediments accumulated in a layer is equal to the total displacement of the layer base corrected for the change in sediment deposition depth.

Prior to computing, the layer thicknesses are to be corrected for the compaction (see, e.g., Bond and Kominz, 1984). It may be necessary also to take into account the change of the layer's thickness during its deformation. The isostatic subsidence (local or regional) is to be subtracted to determine to the pure tectonic component. Dividing this value by the period of layer formation, the tectonic movement rate averaged for the layer formation time may be obtained.

In the general situation allowing both horizontal and vertical movements the paleotectonic method can be applied without correction to those parts of a sedimentary basin where the horizontal component of tectonic movement shows little variation with the spatial coordinates, that is when the horizontal motion is reduced to translational transport of sedimentary cover along a horizontal plane. In this situation, the thickness of the layer at any point of the basin is equal to the vertical displacement of its base with respect to the frame of reference that moves with this point along the horizontal plane. When it is possible to estimate the horizontal movement using independent data, or if an equation linking the horizontal and vertical components of the tectonic movements is invoked, the tectonic rate with respect to a stationary frame also may be obtained.

If the position and the amount of slip on the faults are given, and it is assumed that all displacement accommodated in the faults, the horizontal and vertical rate components become related and both of them can be determined separately. An example of such an approach is the use of detailed seismic data on listric fault systems for extension zones modeling (Gibbs, 1983). It should be noted however that the tectonic rates thus obtained similar to the standard paleotectonic method are averaged for the formation time of each layer. Detailed fault data usually are available for relatively thin sedimentary covers.

This paper is concerned with an approximational method of tectonic-rate determination. In contrast to the standard paleotectonic method, it allows determining nonaveraged rates as functions of spatial coordinates and time. It also allows taking into account the changes in layer thickness during the deformation and, under certain conditions (we discuss them next), to determine the tectonic movement rate not only for the period of sedimentation, but for the period of erosion as well. Some results concerning the uniqueness and stability of the paleotectonic analysis problem were presented by Mikhailov and Myasnikov (1983) and Mikhailov (1989). As an illustration the results of a study of the Terek-Caspian Trough are given.

INPUT DATA

The database for the paleotectonic analysis usually includes data on the present position, thickness, facies composition, and age of sedimentary strata, so it is the same as for a backstripping analysis.

To simplify the mathematical formulae we will consider the two-dimensional problem; the three-dimensional problem is similar. We will use Cartesian coordinates with the Oz axis directed upwards.

Let us assume that the present position of the sedimentary strata is known to us, that is at the present $t = T$, the topographies of the interfaces between the sedimentary strata of different age, $Z_1(x, T)$, $Z_2(x, T)$, . . . $Z_n(x, T)$, the topography of the upper surface (the surface or seafloor topography), $Z^*(x, T)$, and that of the lower boundary (basement or an arbitrary surface considered as a basement of the model), $Z_0(x, T)$, are known functions.

Let us also assume that for each layer placed between interfaces $Z_{i-1}(x, T)$ and $Z_i(x, T)$, we know its period of formation $[t_{i-1}, t_i]$. Facies composition gives information on the depth of the basin at the time of sediment deposition, so usually, the paleorelief $Z_i(x, t_i)$ or some depth interval constraining the paleorelief, $Z_i^d(x) < Z_i(x, t_i) < Z_i^u(x)$, may also be considered as known. Thus, except for eroded segments, we know the position (or interval estimation) of each interface at the time when the overlapping layer started to form and the position at the present time.

FORMULATION OF A PROBLEM

Assume that at a time $t = t_0$ the position of the base of the model $Z_0(x, t_0) = Z^*(x, t_0)$ is given, as well as the horizontal and vertical components of tectonic movement rate $U_0(x, t)$, $W_0(x, t)$ ($t_0 \leq t \leq T$), and the rate of sedimentation $\varphi(x, t)$, equal to the rate of additional supply of material at the upper boundary $Z^*(x, t)$. In addition to the tectonic component, the function $W_0(x, t)$ includes contributions from isostasy and sea-level variations. Being exposed to surface processes, the material at the top of the model suffers disintegration and redeposition. For structures whose characteristic time of development is 1 my or more, it is acceptable to assume that the rate of the land-leveling is proportional directly to the relief gradient $\lambda\, \partial^2 Z^*/\partial x^2$. A detailed analysis of such a model of surface evolution for large-scale structures was described by Mikhailov (1983).

To derive the evolution equations for the geologic interfaces, it is necessary to adopt a straining model involving the mechanical parameters of the material, and the initial and boundary conditions. For the model of the linear-viscous fluid, these equations have the form (Mikhailov, 1983):

$$\begin{cases} \dfrac{\partial Z^*}{\partial t} = \lambda \dfrac{\partial^2 Z^*}{\partial x^2} + \varphi + W_0 - U_0 \dfrac{\partial Z^*}{\partial x} - \dfrac{\partial U_0}{\partial x}(Z^* - Z_0) \\ \qquad + \Psi^*(Z^*, Z_0, Z_k, \mu_k, \rho_k) \\ \dfrac{\partial Z_i}{\partial t} = W_0 - U_0 \dfrac{\partial Z_i}{\partial x} - \dfrac{\partial U_0}{\partial x}(Z_i - Z_0) \\ \qquad + \Psi_i(Z^*, Z_0, Z_k, \mu_k, \rho_k) \qquad k = 1, 2 \cdots n \\ \dfrac{\partial Z_0}{\partial t} = W_0 - U_0 \dfrac{\partial Z_0}{\partial x} \end{cases} \tag{1}$$

As for the initial conditions, it is necessary to specify the function $Z_0(x, t_0) = Z^*(x, t_0)$and the moments of time t_i at which the top of the ith layer $Z_i(x, t_i) = Z^*(x, t_i)$ is formed. The condition of absence of a mass flow through the side boundaries of the model was used as a boundary condition. The functions Ψ^* and Ψ_i contain terms dependent on viscosity (μ_k) and density (ρ_k) of the layers and describe the change of sedimentary layer thickness during deformation. As a consequence of sedimentation and denudation processes, the rate of surface movement is not equal to the rate of the movement of the points situated in its neighborhood. If at some moment $t > t_i$: $Z_i(x, t) < Z^*(x, t)$, that is if the top of the ith layer appears to protrude over the land surface, the surplus is destroyed and it must be assumed that $Z_i(x, t) = Z^*(x, t)$.

ANALYSIS OF UNIQUENESS OF PALEOTECTONIC RATE DETERMINATION

The analysis of the problem of tectonic-rate determination as a function of spatial coordinates and time within the framework of the model (1) has shown that this problem has no unique solution. The solution remains non-unique even if one of the tectonic rate component (U_0 or W_0) is to be known as equal to zero. In (Mikhailov, 1990) it was shown that given the data on thickness, age, and facies composition of the sedimentary layers, it is possible only to determine the total vertical displacement. Any sedimentary structure of arbitrary layer topography and facies composition may be formed by purely vertical tectonic movements and in an infinite variety of ways, provided that the layer topographies remain single-valued functions of coordinates. The same structure may be obtained as a result of different combinations of vertical and horizontal movements.

To obtain a unique solution for the situation of purely vertical movements, it is possible, for example, to confine the solution to a prespecified class of functions. This constraint may be invoked using some general tectonic ideas or using qualitative geodynamical models. As an example, we may note the numerous works on the use of McKenzie's (1978) model, when experimental curves of tectonic subsidence were compared with theoretical curves of thermal lithosphere cooling. Thermal subsidence curves depend mainly on the extension ratio, so the problem to determine the amount of extension on the rift stage is unique and stable.

In the general situation allowing both horizontal and vertical movements, the problem is considerably more complicated. It becomes necessary (but not sufficient) to attach an equation linking the horizontal and vertical components. We have discussed the determination of horizontal and vertical component of tectonic movement with the faults' position and amounts of slip given and all displacement assumed to be accommodated in the faults.

It seems that a promising approach would be to match geodynamical models of lithospheric structure formation with a global evolution model. This would result in additional equations for the lithosphere evolution, one of them linking horizontal and vertical tectonic-rate components with the distribution of temperature and heat generation. The work in this direction is now in progress. Some information is given in Timoshkina (1992).

Further, we will consider the situation of purely vertical movements (more precisely, the case $U_0(x, t) = U_0(t)$). This constraint is not restrictive, because for most sedimentary basins the phases of purely vertical movements account for most of the time of their formation. Let us begin with the simplistic situation, when the functions Ψ^* and Ψ_i in (1) are negligible (for the linear-viscous fluid, it indicated that the changes in stratum thickness during deformation is negligible and that, if $U_0(x, t) = U_0(t)$, the vertical component W_0 is independent of the vertical coordinate z). As demonstrated here, the assumption that the horizontal component is zero is not enough to determine uniquely the vertical tectonic rate as a function of spatial coordinates and time. We shall seek the vertical component as a sum Fourier series:

$$W_0(x, t) = \sum_{l=0}^{L-1} \sum_{k=0}^{K-1} C_{kl} \cos(\pi k x_j) \cdot \sin(\pi l t_i);$$

$$i = 1, 2 \ldots n; \qquad j = 1, 2 \ldots m \tag{2}$$

where the variables x and t are normalized to unit magnitude, m is the number of points along the profile, and n is the number of layers. It is evident that if $K \cdot L \leq m \cdot n$, the problem has a unique solution. The stability of the solution can be achieved by decreasing the number of Fourier series terms.

The idea to seek the solution as a long-period part of the tectonic movement spectrum is in agreement both with experimental geological data and with geodynamical models. As a matter of fact, structures brought about by mantle convection or thermal events are to be regional in terms of spatial scale and to have a long period of formation.

It is seen clearly from Eq. (1) that the functions W_0 and $\varphi(x, t)$ may be obtained separately. We will consider the problem of W_0 determination. As already noted, in the general situation it must be assumed that the paleotopography interval estimates are given at a time $t = t_i$. Then, the determination of the vertical tectonic component is reduced to seeking the Fourier series coefficients satisfying the expressions:

$$\sum_l \sum_k C_{kl} \cos(\pi k x_j) \cdot \int_{t_i}^{1} \cos(\pi l \tau)\, d\tau = \begin{cases} \leq Z_i(x, 1) - Z_i^u(x_j) \\ \geq Z_i(x_j, 1) - Z_i^d(x_j) \end{cases} \tag{3}$$

($t = 1$ is the present time).

We will represent the tectonic movement rate by a 3-dimensional diagrams in the frame (x, t) where x is the distance along the profile and t is the time (Figs. 1 and 2). If some interface had been eroded at the interval $[x_1, x_2]$ and the sediments of the age $t = t_e$ had come beneath the erosion surface, and after the erosion had ended, the sedimentation resumed at a time $t = t_s$, then on the W_0 diagram the period of erosion will be reflected as a "window" $[x_1, x_2]$ by $[t_e, t_s]$, where we have no information on the tectonic rate. If the size of the "window" is smaller than the characteristic W_0 variability wavelength, then the rate of tectonic movement can be determined within this "window" by approximation.

The function W_0 was sought to satisfy the minimum kinetic energy assumption:

$$\int_0^1 \int_0^1 [W_0(x, t)]^2\, dx\, dt = \min \tag{4}$$

under the conditions (3). To solve this problem Zountendijke's method was used (Zountendijke, 1960). For the linear-viscous model (1) the left-hand part of (3) is also a linear function of the coefficients C_{kl} and the method for C_{kl} determination is the same. For more sophisticated rheologies the Eq. (3) are nonlinear, and to solve the problem we are to use the nonlinear minimization methods.

The important differences between the method proposed and the standard paleotectonic analysis method are:

1. The tectonic rate is sought as a function of spatial coordinates and time in nonaveraged form.
2. The rate is determined not only for the period of sedimentation but for that of denudation as well.
3. The thickness changes in the process of deformation can be taken into account within the framework of some mechanical model.

ANALYSIS OF THE TEREK-CASPIAN TROUGH

This example is presented to illustrate the method proposed and to discuss the possible ways of analyzing and interpreting the results. We do not intend to discuss in detail the geodynamics or tectonics of the Terek-Caspian Trough as it is the subject of another publication. The Terek-Caspian Trough is an eastern part of a trough system bounding the Great Caucasus on the north. The trough is filled with a thick sedimentary cover, which has been studied in detail by drilling and seismic prospecting down to the lower Jurassic strata. In most of the trough, the layers are horizontal or slightly inclined, except two anticlinal zones: Terek and Sunzha. The structure of this zone is complicated and the interpretation of seismic data is unreliable. According to the data available, the trough evolution from the Jurassic to the Neogene was associated with vertical movements. The Terek and Sunzha anticlinal zones possibly may be an exception. Formed in the Neogene-Quaternary during the development of the Caucasus Mountain system, they usually are believed to be associated with compression. It is difficult to make any conclusion concerning the earlier history of this structures.

The initial information was taken from a profile intersecting the trough from NNE to SSW near the town of Grozny. Seven sedimentary units were selected from the Early Jurassic to Neogene: $J_2aal - J_3oxf$ (formed from 188 to 156 my b.p.), $J_3kim - tth$ (156–144 my), K_1(144–97.5 my), K_2(97.5–65 my), P_{1-2}(65–38 my), $P_3 - N_1^3$(38.0–17.6 my), and $N_1^3 - N_3^3$(17.6–5.1 my). A paleoreconstruction as of 5.1 my ago was selected as the final stage in the modeling to exclude from consideration the time when the anticlinal zones were formed, apparently the result of horizontal movements.

The total length of the profile was 150 km. The data points along the X axis were spaced apart 3 km. The correction for compaction and isostatic subsidence also was taken into account.

Figure 1 shows a 3-dimensional velocity diagram constructed using the

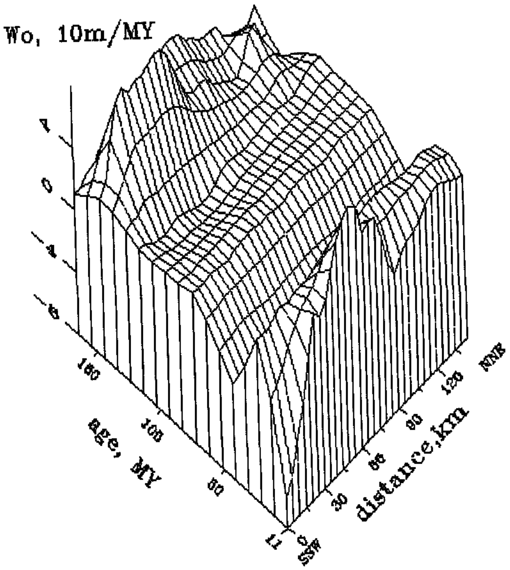

Fig. 1. Vertical tectonic movement-rate component as constructed using averaged tectonic rates. Result is similar to one that might be obtained using standard paleotectonic analysis method. Left-hand axis shows time in my. Right-hand axis presents distance along profile in km. Velocity unit is 10 m/my units. Positive values correspond to subsidence, negative values to uplifting. Caucasus is at $x = 0$.

averaged tectonic velocities. Plotted along the right-hand axis is distance along the profile, and along the left-hand axis, time. The tectonic rate shown in the diagram was determined as the thickness of the layer with corresponding corrections divided by the duration of its formation period. For each unit, these values were assigned to the middle of the formation time interval (163.5 my before present, 150.0, 121.0, 78.8, 49.9, 28.0, and 12.0) It is easy to see that Fig. 1 is just another format to present the results obtained by applying the standard paleotectonic method. It also is seen clearly that the geological information is distribution non-uniformly in time. The Jurassic ($t > 144$ my) and the Early Paleogene to Neogene interval ($38.0 < t < 5.1$ my) are represented in detail with an average data specification interval (unit formation time) from 10 to 20 my. In contrast, the time interval from the Early Cretaceous to the end of Middle Paleogene is represented by only three stratigraphic subdivisions; the mean data specification interval increases to 30 my and more. As a result, the velocities in the diagram are averaged during the time intervals from 144 my to

38 my so large that the analysis of the velocity field becomes virtually impossible.

In the process of solving the problem (3)–(4) a series of numerical experiments were carried out to estimate the effects of truncating the Fourier series (2) in x and t. In all the experiments regardless of K and L much of the energy was carried by the leading 6–7 time terms and most in about 10 x-terms. When a number of K and L was reduced, the function W_0 became smoother, but its main features were tolerant to changes in K and L. The computing stability also was tested by running the program with the double-size step along the x-axis (6 km) and a more detailed stratigraphic subdivisions of Jurassic and Neogene-Paleogene. Figure 2 shows the results of calculations for Fourier series with 25 terms in x and 6 terms in t is shown. We will return to the discussion of numerical stability later. The model of viscous fluid (1) was used to account for the changes in layer thicknesses during the deformation. Because the layers have had a gentle dip throughout the trough evolution time, the changes in layer thicknesses were negligible for the layer viscosities of about 10^{19} Pa · s.

A comparison between the two diagrams shows they are in agreement in regions where detailed data were available. For the time interval from 140 to 60 my, interpolation based on the diagram Fig. 1 is problematic. In this region,

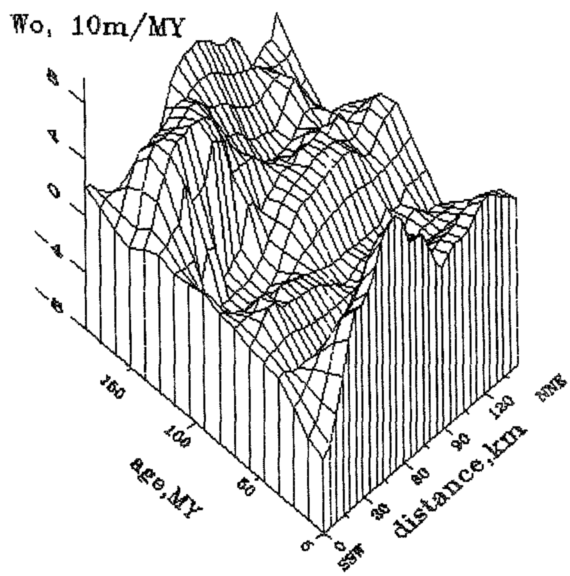

Fig. 2. Vertical tectonic movement-rate component as obtained using numerical method (3)–(4). Notation and explanation are in Fig. 1.

this diagram is to smoothed and all peculiarities in the behavior of the function W_0 are lost.

As shown in Fig. 2, the uplifting and subsidence occur on segments spanning from 40 to 50 km along the profile and have a characteristic duration of 30 to 40 my. The highest velocity value at time interval $t < 15$ my is associated with Caucasus orogeny (Caucasus is at $x = 0$). The wave-like character of the motion is traced easily in time: as we move from t-axis, it is possible to observe on each segment of the profile as the ascending and descending movements start and develop, then gradually attenuate and are replaced by movements of the opposite sign. In the Jurassic and a great part of the Cretaceous, the southern ($x = 0$) and northern ($x = 150$) parts of the profile seem to have moved in antiphase: when the southern part of the profile was subsiding, a corresponding uplift was developing in the northern part, and *vice versa*. The same pattern, but in a smoothed form, can also be seen in Fig. 1.

Figure 3 shows the subsidence curve obtained using the tectonic rate averaged for the profile:

$$W_{ev}(t) = \int_0^1 W_0(x, t)\, dx \tag{5}$$

With the exception of an early period of orogeny in the Caucasus, this curve is similar to the thermal subsidence curve obtained for most extensional sedimen-

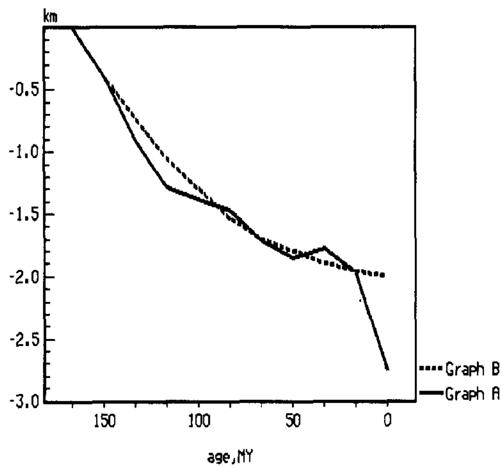

Fig. 3. Overall subsidence curve $W_{ev}(t)$ for entire profile. Horizontal axis represents time in my, vertical axis, depth in km. Graph A—experimental subsidence curve; Graph B—bestfitting thermal subsidence curve.

tary basins. The best-fitting thermal subsidence curve is shown with the dotted line.

The deviations of the tectonic rate from the averaged curve: $W_{loc}(x, t) = W_0(x, t) - W_{ev}(t)$ is shown in Fig. 4. This diagram shows the local features of evolution of individual parts of the trough against the background of the overall subsidence. It is seen more clearly in this diagram than in the previous one that the movement of the northern and southern parts of the profile occurred in antiphase. The boundary between these sectors passes along the Pshekish-Tyrnyaus deep-seated fault. Its position is shown on the x axis. The Sunzha anticlinical zone is situated in the sedimentary cover over this fault. This fault is seen clearly in gravity and magnetic maps, in the seismic profiles, and on the diagram of local tectonic movements. According to the results obtained here, this fault has controlled the trough evolution for approximately 200 my.

Such a character of the local component behavior may be explained either by local or regional tectonic processes. To explain the antiphase movement of the southern and northern parts of the profile, let us suppose that this fault is not vertical. In this situation, during a regional compression one side will move upward and the other one downward. When the compression is removed or during extension the sense of movement will be opposite.

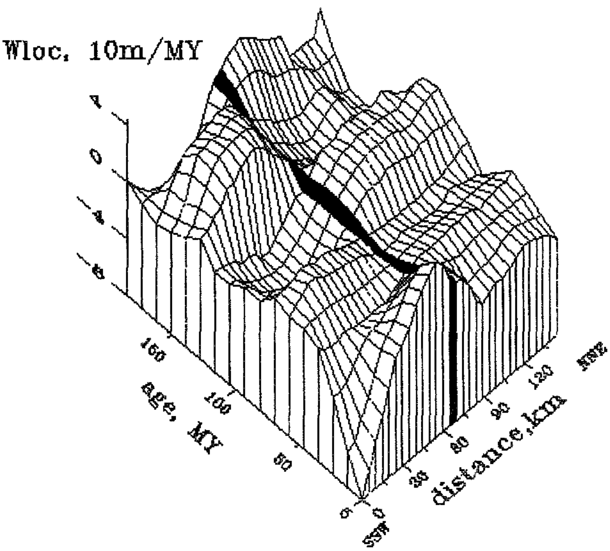

Fig. 4. Local component of tectonic movements against background of overall subsidence (Fig. 3): $W_{loc}(x, t) = W_0(x, t) - W_{ev}(t)$. Notation is same as in Fig. 1. Shaded area is position of Pshekish-Tyrnyaus deep-seated fault.

This interpolation does not contradict the assumption that the tectonic movements have been vertical because the sedimentary cover is relatively thin in comparison with the horizontal extension of the trough. The horizontal component of velocity in the sediments would not depend on the spatial variables with the exception of the narrow zone above the deep-seated fault. The effect of the horizontal component thus is confined to producing a simple horizontal transfer of the great part of the trough.

It is important to mention that in numerical experiments with different values of K, L, n, and m, the behavior of $W_0(x, t)$ and $W_{loc}(x, t)$ has conformed to the pattern: the subsidence was slowing (Fig. 3), whereas the northern and southern parts of the profile were involved in antiphase motion. The period of velocity oscillations ranged from 60 to 80 my, which is close to that of last term ($L = 6$) in Eq. (2), that is 36 my. However, this latter number may not be reliable and is to be checked by calculations from the other profiles.

CONCLUSION

The proposed method of paleotectonic analysis is based on representing the tectonic-movement rate as a sum of a function series depending on the spatial coordinates and time. It is possible to use this method with various models: of viscous fluid (1), of elastic or plastic media. It allows using the equations linking horizontal and vertical components of tectonic movements. These equations may be obtained as a result of matching the geodynamical models of lithosphere structure formation with the global evolution model or with data on fault position and amount of slip. Depending on the problem, the equations forming set (3) may be linear, and may require more complicated methods of solution. But in any situation it will be necessary to determine a finite set of coefficients C_{kl} which will provide for the uniqueness and stability of the paleotectonic problem. Such an approach makes it possible to retrieve the velocity field with considerably greater detail than the conventional paleotectonic analysis method, and to estimate the rate of movements during erosion periods.

The analysis of the tectonic movement rate for the Terek-Caspian Trough showed that its tectonic-movements rate has comprised two components: the overall subsidence slowing down as a square root of time and the local component which shows the antiphase movement of northern and southern parts of profile. The local component has been controlled by a deep-seated fault since at least the Jurassic.

ACKNOWLEDGMENTS

I am thankful to Prof. N. Kornovskij and Dr. L. Panina, who provided the interpreted cross-section and the paleorelief data.

REFERENCES

Beloussov, V. V., 1938, Great Caucasus (In Russian): Trudi CNIGRI, No. 108, 98 p.

Beloussov, V. V., 1980, *Geotectonics*: Mir-Springer, Moscow, 330 p.

Bond, G. C., and Krominz, M. A., 1984, Construction of Tectonic Subsidence Curves for Early Paleozoic Miogeocline, Southern Canadian Rocky Mountains: Implications for Subsidence Mechanism, Age of Breakup, and Crustal Thinning: Geol. Soc. Am. Bull., v. 95 n. 1, p. 155–173.

Gibbs, A. D., 1983, Balanced Cross-Section Construction from Seismic Sections in Area of Extensional Tectonics: J. Struc. Geol., v. 2 n. 2, p. 153–160.

Mckenzie, D. P., 1978, Some Remarks on the Development of Sedimentary Basins: Earth Planetary Sci. Lett., v. 40 n. 1, p. 25–32.

Mikhailov, V O., 1983, A Mathematical Model of the Process of Evolution of Structures Formed as a Result of Vertical Tectonic Movements: Physics of the Solid Earth, ''Izvestya'' Acad. Sci., USSR, v. 19 n. 6, p. 431–441.

Mikhailov, V. O., 1989, Mathematical Method for Solving Paleotectonic Analysis Problem: Phys. Solid Earth, ''Izvestya'' Acad. Sci., USSR, v. 25 n. 3, p. 235–244.

Mikhailov, V. O., and Myasnikov, V. P., 1983, Contribution on Mathematical Theory of Paleo Analysis: Proc. (Doklady) Acad. Sci., USSR. Earth Sci. Sect., v. 270 n. 3, p. 31–33.

Timoshkina, E. P., 1992, Models of Lithosphere Matched with Global Geodynamical Model: Effects of Mantle Flow in the Thermal Structure and Mechanical Evolution of Continental Lithosphere: Abst. EGU Ann. Meeting: Ann. Geophys., v. 10 (Suppl. I), pt. I, p. 86.

Zountendijke, G., 1960, Method of Feasible Directions: American Elsevier, New York, 260 p.