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## GEOPHYSICS

# Identification of Crustal Blocks Based on GPS Data

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The style of the continental crust deformation is nowadays the most discussed topic of geodynamics [1]. According to one concept, the lithosphere is an assemblage of microplates (blocks) and its deformation is caused by displacements along the block boundaries (see, for example, [2]). According to an alternative concept, the lithosphere deformation is distributed throughout the volume and corresponds to a rheological model of nonlinear viscous fluid (see, for example [3]). The discussion stems mainly from materials related to Asian regions involved to a certain extent in the process of collision of the Indian and Eurasian plates [2, 3]. The adequacy criterion of either concept is not quantitatively strictly formalized.

This paper, which is based on data of the Central Asian GPS network incorporating over 450 observation points, examines the problem of identification of blocks in the spatial velocity field of modern horizontal motions. The blocks are understood as 2D areas, the motion of which is similar to their motion as rigid bodies in a certain sense specified below. The problem of identification of blocks was first considered in [4], in which blocks were delineated on the basis of the maximum similarity of the vectors of horizontal linear velocities $\mathbf{v}^{(i)}$. In the present paper, we made a fundamental modification in the approach in order to ensure invariance of results relative to the choice of the reference frame, which is taken as an absolutely rigid body in classical mechanics.

Figure 1 shows the variability of the velocity field upon change in the reference frame. Block identification based on the criterion of closeness of velocities $\mathbf{v}^{(i)}$ in value and direction is liable to produce dissimilar results upon change in the reference frame.

If the earth's crust has a block structure, the number and shape of blocks are intrinsic features that cannot (and must not, if the solution is correct) depend on the extrinsic procedure of choosing the reference frame. The above statement is a rewording of the principle of independence of the observer (see, for example, [5]), which requires that the intrinsic features of a medium (constitutive equations, structure, and so on) should be invariant relative to Galilean transformations ("rigid" motions).

Let us first examine the auxiliary problem of defining the characteristics of the plane motion of a rigid body **E** relative to a certain reference frame. The plane motion at any moment of time can be visualized as its rotation with the angular velocity vector **w** relative to the instantaneous pole $C$ with the radius vector $\mathbf{x}^C$ [6]. Let the given body **E** incorporate $N \geq 3$ points with radius vectors $\mathbf{x}^{(i)}$ with known vectors $\mathbf{v}^{(i)}$ of linear velocities relative to the chosen reference frame. Velocities $\mathbf{v}^{(i)}$ are written as

$$\mathbf{v}^{(i)} = \mathbf{w} \times (\mathbf{x}^{(i)} - \mathbf{x}^C), \quad i = 1, 2, \ldots, N. \tag{1}$$

The problem consists in specifying the vectors **w** and $\mathbf{x}^C$ based on the given $\mathbf{v}^{(i)}$ (the direction **w** being vertical for plane motion). This problem can be solved by different methods, including a variational one, which consists in minimization of the functional $J_1$:

$$J_1 = \frac{1}{N}\sum_{i=1}^{N}\left|\Delta\mathbf{v}^{(i)}\right|^2, \quad \Delta\mathbf{v}^{(i)} = \mathbf{v}^{(i)} - \mathbf{w} \times (\mathbf{x}^{(i)} - \mathbf{x}^C), \tag{2}$$

where $\Delta\mathbf{v}^{(i)}$ is the difference between the observed velocity vector and the vector calculated from (1) at the point $\mathbf{x}^{(i)}$. In the posed auxiliary problem, the minimum value $J_1$ is known to be equal to zero. The vectors **w** and $\mathbf{x}^C$ that minimize the functional $J_1$ are found from the solution of a system of algebraic equations based on the conditions

$$\frac{\partial J_1}{\partial \mathbf{w}} = 0, \quad \frac{\partial J_1}{\partial \mathbf{x}^C} = 0. \tag{3}$$

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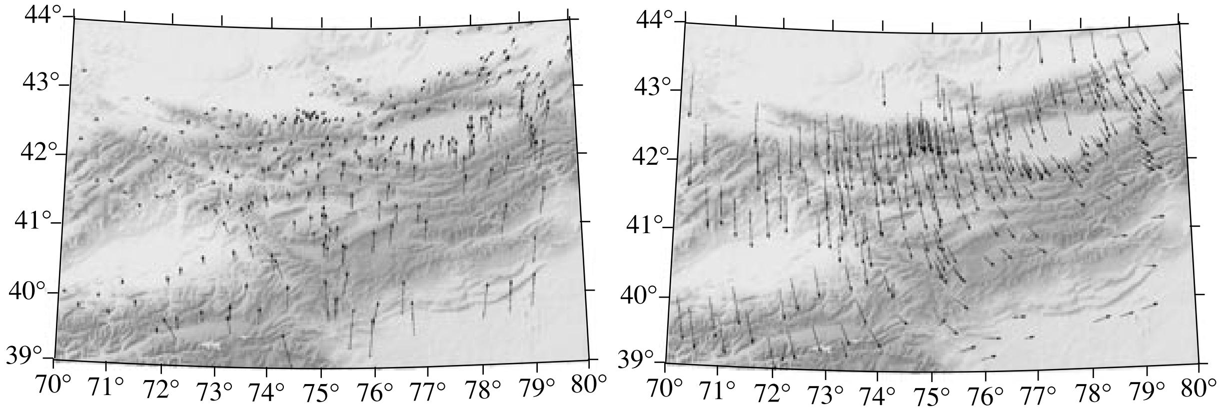


**Fig. 1.** Vector field of velocities of the Central Asian GPS network relative to stable parts of the Eurasian Plate (left image) and to the reference frame rotating clockwise with angular velocity $|\mathbf{w}| = 2$ ms/yr around the immobile (in the Eurasian reference frame) pole $\mathbf{x}^C$ with coordinates $x_1^C = 95°$ E, $x_2^C = 46°$ N (right image).

The block identification problem (the principal problem) differs from the auxiliary one in two fundamental aspects: (a) within each block, condition (1) may not be fulfilled owing to both errors of the measurement of vectors $\mathbf{v}^{(i)}$ and the possible deformation of blocks; (b) it is unknown in advance which of the GPS stations (i.e., points $\mathbf{x}^{(i)}$ with the given velocities $\mathbf{v}^{(i)}$) will be incorporated in a certain block. Nevertheless, it seems possible to generalize the above-described variational approach in order to take into account the noted variances of the principal and auxiliary problems. Let us introduce the following definition: the maximum simply connected earth's surface area $\Omega$ with sufficiently smooth boundary is a 2D block (GPS block) if

$$J_1^* = \sqrt{\min_{\mathbf{x}^C, \mathbf{w}} J_1} \le J_{\max}^*. \quad (4)$$

Here, $\min_{\mathbf{x}^C, \mathbf{w}} J_1$ is the minimum value (relative to the choice of vectors $\mathbf{x}^C$ and $\mathbf{w}$) of the functional $J_1$ in (2) calculated from the data of $N$ ($N \ge 3$) GPS stations which pertain to the area $\Omega$; $J_{\max}^*$ is the block structure parameter, which characterizes the maximum permissible difference of the velocities in $\Omega$ from the rigid motion velocities. The vectors $\mathbf{x}^C$ and $\mathbf{w}$ that return a minimum to the functional $J_1$ are calculated from (3). They represent the averaged radius vector of the pole and the averaged angular velocity for the identified block.

In addition to the functional $J_1$, it is also possible to choose other criteria that specify the measure of deviation of block velocities from rigid body velocities. The functional $J_2 = \max_i |\Delta\mathbf{v}^{(i)}|$, for instance, is the maximum module of the velocity deviation from rigid motion throughout the totality of points $\mathbf{x}^{(i)}$ in a block. If we use the functional $J_2$, the block existence criterion is written as

$$J_2^* = \min_{\mathbf{x}^C, \mathbf{w}}(\max_i |\Delta\mathbf{v}^{(i)}|) \le J_{\max}^*. \quad (5)$$

Solution of the principal problem requires the sorting of all stations and their grouping into blocks. In order to combine the stations into groups, one can apply hierarchic cluster analysis methods subdivided into ascending and descending ones [7]. The ascending version is easier, because it does not require a great amount of sorting for splitting the set of points into a number of groups, whereas the descending version is more resistant to measurement errors. We developed an algorithm based on a combined method of ascending/descending hierarchical grouping of velocity vectors of closely located observation points. This algorithm allows exchange of points between blocks. Spatial closeness of points is determined from a triangulation network performed by GMT software [8] based on the "optimal Delaunay triangulation" method. Amongst the multitude of possible vector grouping combinations, we

**Table**

| Block no. | Number of points in block | Angular velocity $|\mathbf{w}|$ (ms/yr) | Pole coordinates $\mathbf{x}^C$, degree | |
|---|---|---|---|---|
| | | | E | N |
| 1 | 4 | 1.66 | 53.883 | 41.176 |
| 2 | 72 | −0.14 | −13.989 | −0.321 |
| 3 | 3 | 8.07 | 68.316 | 37.888 |
| 4 | 10 | −2.11 | 99.942 | 35.411 |
| 5 | 41 | 2.47 | 47.869 | 40.254 |
| 6 | 44 | 0.93 | 164.775 | 42.107 |
| 7 | 105 | 0.09 | 58.046 | −0.327 |
| 8 | 33 | 0.30 | 58.046 | 47.595 |
| 9 | 8 | 0.47 | 11.472 | 23.361 |

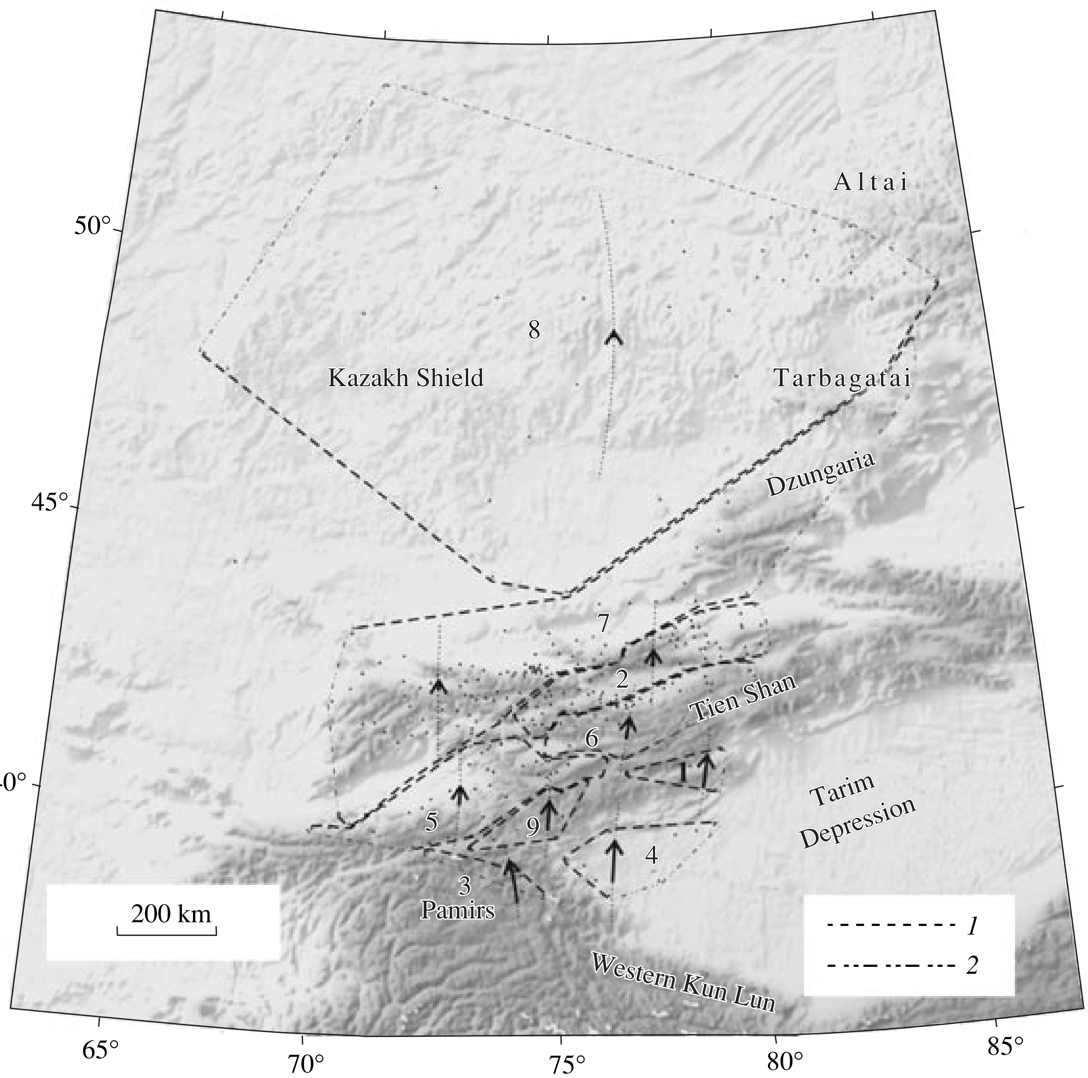


**Fig. 2.** Kinematic model of the block structure of the Central Asian crust based on GPS data (1995–2004). The maximum permissible velocity deviation from the velocities of ideally rigid blocks is 3 mm/yr. Block boundaries: (*1*) within the GPS measurement area; (*2*) arbitrarily drawn boundary along the GPS network periphery; numerals correspond to block numbers; arcs designate block rotation trajectories relative to the stable part of Eurasia; arrows (with consideration of length) designate directions and relative linear velocities; small triangles designate GPS stations involved in the clusterization.

choose those combinations which return the minimum to the grouping functional $J_1^*$ or $J_2^*$.

Numerical simulations have shown that the block existence criterion (5) is preferable to criterion (4). In criterion $J_1^*$, blocks with a multitude of observation points can incorporate particular stations, velocity vectors of which substantially differ from the motion of a rigid body. The level of block structure specification is controlled by the critical value $J_{\max}^*$. Increasing $J_{\max}^*$ leads to scaling up of blocks and, vice versa, decreasing $J_{\max}^*$ makes it possible to reveal details of the velocity field structure.

In order to examine the structure of modern velocity fields of the studied territory, we used data on measurements in 1995–2004 at stations with the velocity measurement error better than 1 mm/yr. The $J_{\max}^*$ value was taken to be 3 mm/yr. This level of generalization made it possible to identify nine blocks in the studied territory. Their boundaries along the GPS network periphery are shown arbitrarily. Characteristics of the block motion relative to the stable part of Eurasia are presented in Table 1 and Fig. 2. The angular velocity is considered positive if the rotation is counterclockwise. The presented results show that the northwestern part of the Pamirs (Block 3) and the adjacent western part of the Tarim sector (Block 4) are moving asymmetrically in relation to the selected reference frame: the Pamirs sector shows a counterclockwise rotation and NNW-oriented drift, whereas the Tarim sector shows a clockwise rotation and NNE-oriented drift. Northward of the

Pamirs and Tarim, one can see a distinct NE-oriented intense deformation zone up to 400 km wide. It incorporates Tien Shan and extends via the Dzungar and Tarbagatai ridges to the Altai fold system (blocks 1, 2, 5–7, 9). All these blocks, except for Block 2, have a minor counterclockwise rotation. Block 2, embracing the northern part of the central Tien Shan, shows a slow clockwise rotation (0.14 ms/yr). Northwestward of the deformation zone, one can see a vast and stable territory of the Kazakh Shield (Block 8) showing a minor counterclockwise rotation (0.3 ms/yr).

Thus, we propose an objective method for revealing the crust fragmentation based on space geodesy data. At the chosen scale level controlled by parameter $J^*_{\max}$, the heterogeneous field of the modern horizontal velocity field of the Central Asian crust appears as an aggregate of low-deformable blocks and a relatively restricted interblock space. The main (including seismotectonic) deformations of the region are concentrated in the interblock space. The obtained block motion picture reflects the dynamic influence of the Indian Plate, thus attesting to the adequacy of the obtained block structure. Nothing purports that the detected GPS blocks must completely coincide with the blocks delineated on the basis of geological observations. GPS blocks characterize instantaneous (over a time span of 1 to 10 yr) features of crust motion. The block configuration can change owing to a number of large earthquakes, entailing additional discontinuities in the velocity field. Geological blocks reflect the cumulative effect of instantaneous motions over long-term periods.

Let us note the following essential feature of our model. If the block structure parameter $J^*_{\max}$ is fixed, the picture of motion of blocks (and sometimes their number) is apt to change in some details with change in the number of GPS stations involved in the analysis. Some instability of the results thus detected probably has a physical nature, suggesting that the simple alternative of block structure or continuous deformation does not exhaust all actual crust deformation styles. It is quite probable that the velocity field of the Central Asian region has a scale-invariant (fractal) structure, making it hard to image it as a system of single-scale blocks.

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## REFERENCES

1. W. Thatcher, Int. Geol. Rev. **45**, 191 (2003).
2. J.-P. Avouac and P. Tapponier, Geophys. Res. Lett. **20**, 895 (1993).
3. P. England and P. Molnar, Science **278** (5338), 647 (1997).
4. A. V. Zubovich, R. T. Beisenbaev, W. Saochan, et al., Fiz. Zemli, No.9, 31 (2004).
5. C. Trusdell, *A First Course in Rational Continuum Mechanics* (Prentice Hall, New York, 1975; Mir, Moscow, 1975).
6. M. A. Aizerman, *Classical Mechanics* (Nauka, Moscow, 1974) [in Russian].
7. M. Jambu, *Classification automatique pour l'analyse des donnes* (Borda, Paris, 1978; Finansy Statistika, Moscow, 1988).
8. P. Wessel and W. H. F. Smith, *The Generic Mapping Tools (GMT). Version 3.0 Technical Reference & Cookbook* (SOEST/NOAA, New York, 1995).