FAULT MORPHOLOGY RECOGNITION BY DIGITAL ELEVATION MODEL PROCESSING

Igor V. Florinsky

Institute of Mathematical Problems of Biology, Pushchino, Moscow Region, 142292, Russia

Commission IY, Working Group 4; Commission YII, Working Group 4

KEY WORDS: Geomatic, Geology, DEM, Analysis, Fault, Morphology, Recognition, Topography

ABSTRACT:

A quantitative method of morphology recognition of topographically expressed faults is developed. The method is based on digital elevation models (DEMs) analysis. Lineaments revealed on horizontal landsurface curvature maps indicate faults formed mostly by horizontal tectonic motions (i.e., strike-slip faults). Lineaments recognised by vertical landsurface curvature mapping correspond to faults formed mainly by vertical motions (i.e., dip-slip and reverse faults) and thrusting. Lineaments recorded on both horizontal and vertical curvatures maps indicate, as a rule, oblique-slip and gaping faults. The method is tested by processing the DEMs of an abstract area with modelled faults and a DEM of a part of the Crimean Peninsula and the adjacent sea bottom.

1. INTRODUCTION

Faults can be revealed by several geological, geophysical, remote sensing and topographical techniques (Slemmons, Depolo, 1986). As tectonic motions can result in linear deformations of the landsurface so topographically expressed lineaments are often used as fault indicators (Hobbs, 1904; Ollier, 1981). Properties of linear relief dislocations formed by vertical tectonic motions differ from properties of topographic lineaments which are horizontal movement traces (Trifonov, 1983). Qualitative and quantitative signs of these differences can be used as a basis for fault morphology recognition.

Qualitative approaches to revealing and morphological classification of faults by a relief analysis were often exploited (Trifonov, 1983; Slemmons, Depolo, 1986). Of frequent use was a visual analysis of topographic map contours (Hobbs, 1904; Phylosophov, 1960) and remotely sensed images (Wilson, 1941; Trifonov et al., 1983). Keller (1986) summed up data on qualitative geomorphic indices of active faults. Stereophotogrammetric analytical techniques were applied for fault revealing, morphological recognition, dip and strike measuring (Vinogradova, Yeremin, 1971).

Indicated qualitative approaches are not free of subjectivity. However, due to difficulties in formalization of fault geomorphic indices there are a lot of quantitative computer methods of fault revealing by remotely sensed (Burdick, Speirer, 1980; Masuoka et al., 1988) and topographic data processing, but there is no quantitative method for fault morphological classification by outlined data handling without ancillary geological information.

Digital elevation models (DEMs) and DEM analysis methods are used for fault recognition as about 90% of fault geomorphic indices can be defined quantitatively (Schowengerdt, Glass, 1983). There are techniques of perspective views (Campagna et al., 1991), thalvegs revealing (Eliason, Eliason, 1987), landsurface gradient and aspect mapping (Onorati et al., 1992), reflectance mapping (Wise, 1969; Schowengerdt, Glass, 1983). DEMs are applied for measuring dip and strike of known faults (Chorowicz et al., 1991). However, the use of indicated methods of DEMs analysis without ancillary geological data does not permit us to determine a fault morphology.

Reproducible recognition of lineaments can also be obtained by calculation and mapping of the horizontal (Kh) and vertical (Kv) landsurface curvatures with the use of DEMs (Florinsky, 1992). Statistical properties of lineaments (i.e., orientation, length, density) recorded on Kh maps are rather different from statistical properties of linear structures revealed by Kv mapping (Florinsky, 1992). Taking into account physical and mathematical senses of Kh and Kv (Evans, 1980; Shary, 1991) we can reason that lineaments revealed by Kh mapping correspond mostly to structures like strike-slip faults, while lineaments revealed by Kv mapping indicate mainly structures as dip-slip faults and thrusts.

2. THEORETICAL BASIS OF THE METHOD

Let us consider a surface klmp. Kv is the curvature of a normal section bac of the surface klmp. The section bac includes a gravity acceleration vector g and a normal vector n in a given point a. Kh is the curvature of a normal section dae of the surface klmp. The section dae is perpendicular to the section bac and includes the normal vector n in the given point a. If indicated sections are convex Kh and Kv have positive values, if sections are concave Kh and Kv have negative ones, if sections are plane Kh and Kv have zero values (Evans, 1980; Shary, 1991).

Suppose a dip-slip (or reverse) fault is formed within the surface klmp. Kh and Kv values within the scarp zone will change and besides Kv will have negative values all along a fault line. Let us stratificate Kh and Kv values into two levels with respect to the zero value and paint areas with Kh and Kv positive values in white colour, while areas with negative values of curvatures in black colour. An indicator of the dip-slip (or reverse) fault that is a black lineament on a white background will be recorded on the Kv map. A similar lineament will be recognised on the Kv map if before a vertical motion a surface was plane. If before vertical motion Kv values were negative the Kv sign will also change along the fault line therefore a white lineament on a black background on the Kv map will indicate a dip-slip fault. A lineament consisting of black and white lines and spots will be recorded on the Kv map after a vertical movement if a surface has a complicated form. In a like manner, a lineament indicating a thrust will be revealed on the Kv map since thrusting also brings into existence a scarp, as a rule.

However, lineaments indicating dip-slip, reverse and thrust faults will not be recorded on the Kh map because changes of the Kh sign along lines of these faults will be random rather than systematic. At the same time, some non-lineament changes on the Kh map will arise.

Suppose a strike-slip fault is formed within the surface klmp. Kh and Kv values will also change in the deformation zone. The Kh will take negative values along all the fault line, while changes of the Kv sign will be random rather than systematic. Consequently, the following lineaments indicating horizontal movement traces will be recorded on the Kh map: a) a black lineament on a white background for a surface with positive Kh value and for a plane surface, b) a white lineament on a black background for a surface with negative Kh values, and c) a lineament consisting of white and black lines and spots for a complex surface. Some non-lineament traces of horizontal movements will be recorded on the Kv map.

After an oblique-slip and a gaping faults formation both Kh and Kv ought to change sign systematically along fault lines. Therefore, we can anticipate that lineaments indicating these faults will be recorded on both the maps.

The method proposed has the following limitations:
1. It is impossible to determine and separate lineaments of non-tectonic (i.e., erosion, eolian) origin without ancillary geological, geophysical and geomorphic data.
2. Lineaments recorded on Kh and Kv maps can be connected with flexures and folds. To determine and separate these lineaments ancillary non-topographic data have to be used too.
3. If a strike-slip fault is located along a surface strike a lineament cannot be recorded by Kh mapping.
4. We also have to use ancillary geological data to separate: a) a dip-slip, reverse and thrust faults equally revealed on Kv maps and b) an oblique-slip and gaping faults equally revealed on both Kh and Kv maps.

Kh and Kv digital models are obtained by DEMs processing. To reveal topographically expressed faults within a certain scale range DEM has to be compiled by regular net and DEM resolution has to correspond to a typical plan size of faults under study.

3. METHOD TESTING

To test the method developed we used the DEMs of an abstract area with modelled faults and a DEM of a part of the Crimean Peninsula and the adjacent sea bottom.

3.1 The Abstract Area

3.1.1 Study Site: The abstract area (Fig. 1 a) has sizes of 60 m x 60 m. It includes a single near-east oriented valley two watersheds. Elevation amplitude is 7.5 m.

3.1.2 Initial Data and Methods: The irregular DEM of the abstract area was compiled (Fig. 1 a). Five simple typical faults were modelled by deformation of the initial irregular DEM: a vertical dip-slip fault with 1 m displacement (Fig. 1 d), a left-lateral strike-slip fault with 3.5 m displacement (Fig. 1 g), an oblique-slip fault with 3.5 m left-lateral horizontal and 1 m vertical displacements (Fig. 1 j), a overthrust with 15 m displacement (Fig. 1 m), a gaping fault with a trench of 1 m width and 0.2 m depth (Fig. 1 p). Five irregular DEMs with indicated modelled faults were obtained.

Regular DEMs of initial and deformed surfaces were generated by the Delaunay triangulation and piecwise polynomial smooth interpolation of corresponding irregular DEMs. The matrix step 2 m was used. Kh and Kv digital models (Fig. 1 b, c, e, f, h, i, k, l, n, o, q, r) for regular DEMs were calculated by the algorithm of Evans (1980).

3.2 The Part of the Crimean Peninsula and the Adjacent Sea Bottom

3.2.1 Study Site: The study site (between Latitudes 44°21' N - 45°30' N and Longitudes 33°13' E - 35°55' E) has sizes of 210 km x 132 km. We chose this region to test the method developed by two reasons. First, it is one of the best studied areas in the world (Muratov, 1969; Beloussov, Volvovsky, 1989). There are a lot of factual geological, geophysical and remotely sensed data to test fault revealing and morphology recognition. Second, a diversity of relief and tectonic structures within the region allow us to test the method in different topographic and geological conditions.

The structure of the study site is complicated by a lot of faults. The following main fault groups can be distinguished (Muratov, 1937; Shalimov, 1966; Rastsvetaev, 1977; Borisenko, 1986):
1. Near-north-striking left-lateral strike-slip faults with high-angle dips, 3-5 kilometres horizontal displacements and tens of kilometres lengths. They most abundant in the east, central and south-west parts of the study site.
2. Near-north-east and east-striking dip-slip faults with north-west dips and tens of meters displacements. Some researchers consider that these faults are trusts with 30°-45° dips and several kilometres displacements.
3. Near-north-west-striking dip-slip and oblique-slip faults with high-angle dips. Oblique-slip faults have right-lateral 10-100 meters horizontal displacements.
4. Near-north-striking dip-slip faults located in the west part of the region.

3.2.2 Initial Data and Methods: To test the method the irregular DEM of the part of the Crimean Peninsula and the adjacent sea bottom was applied. This DEM was compiled by digitising 1:300000 and 1:500000 scaled topographic maps (Florinsky, 1992). The regular DEM (Fig. 2 a) was generated by the irregular DEM interpolation using the weighted average method. The matrix step 500 m was used. Kh and Kv digital models (Fig. 2 b, c) were obtained by the algorithm of Evans (1980) using the matrix step 3000 m.

The map of revealed and morphologically classified faults (Fig. 2 d) was obtained by a visual analysis of the Kh and Kv maps (Fig. 2 b, c). To estimate efficiency of the method we carried out a visual comparative analysis of the obtained fault map (Fig. 2 d) and some factual geological data (Moisejew, 1930, 1939; Muratov, 1937, 1969; Lebedev, Orovetsky, 1966; Shalimov, 1966; Rozanov, 1970; Rastsvetaev, 1977; Sollogub, Sollogub, 1977; Sidorenko, 1980; Kats et al., 1981; Kozlovsky, 1984; Borisenko, 1986; Zaritsky, 1989).

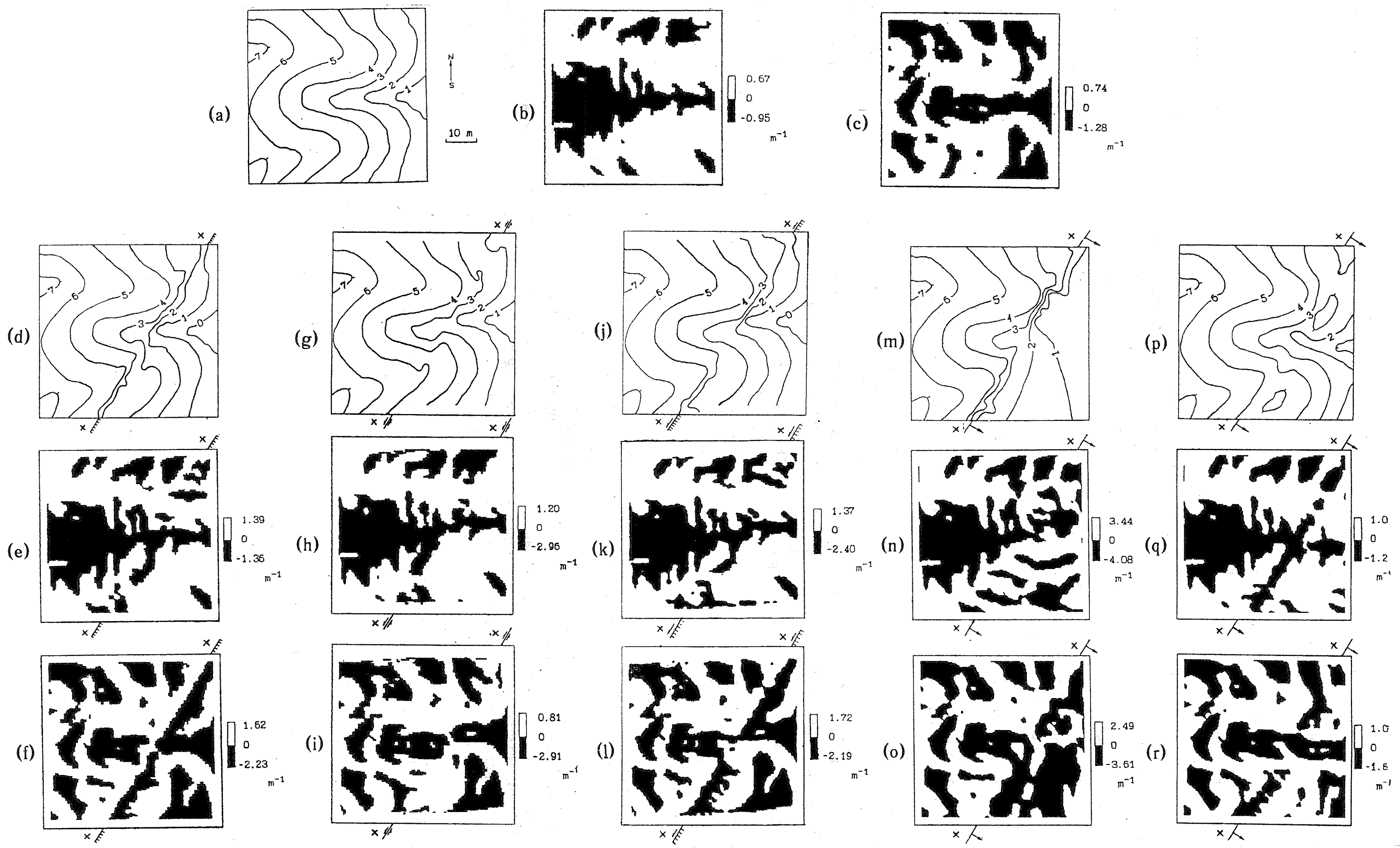

Fig. 1. Maps of the abstract area with modelled faults, *x-x* are fault axes: (a) - elevations of the undeformed area, (b) - Kh of the undeformed area, (c) - Kv of the undeformed area, (d) - elevations of the area with the dip-slip fault, (e) - Kh of the area with the dip-slip fault, (f) - Kv of the area with the dip-slip fault, (g) - elevations of the area with the strike-slip fault, (h) - Kh of the area with the strike-slip fault, (i) - Kv of the area with the strike-slip fault, (j) - elevations of the area with the oblique-slip fault, (k) - Kh of the area with the oblique-slip fault, (l) - Kv of the area with the oblique-slip fault, (m) - elevations of the area with the overthrust, (n) - Kh of the area with the overthrust, (o) - Kv of the area with the overthrust, (p) - elevations of the area with the gaping fault, (q) - Kh of the area with the gaping fault, (r) - Kv of the area with the gaping fault.

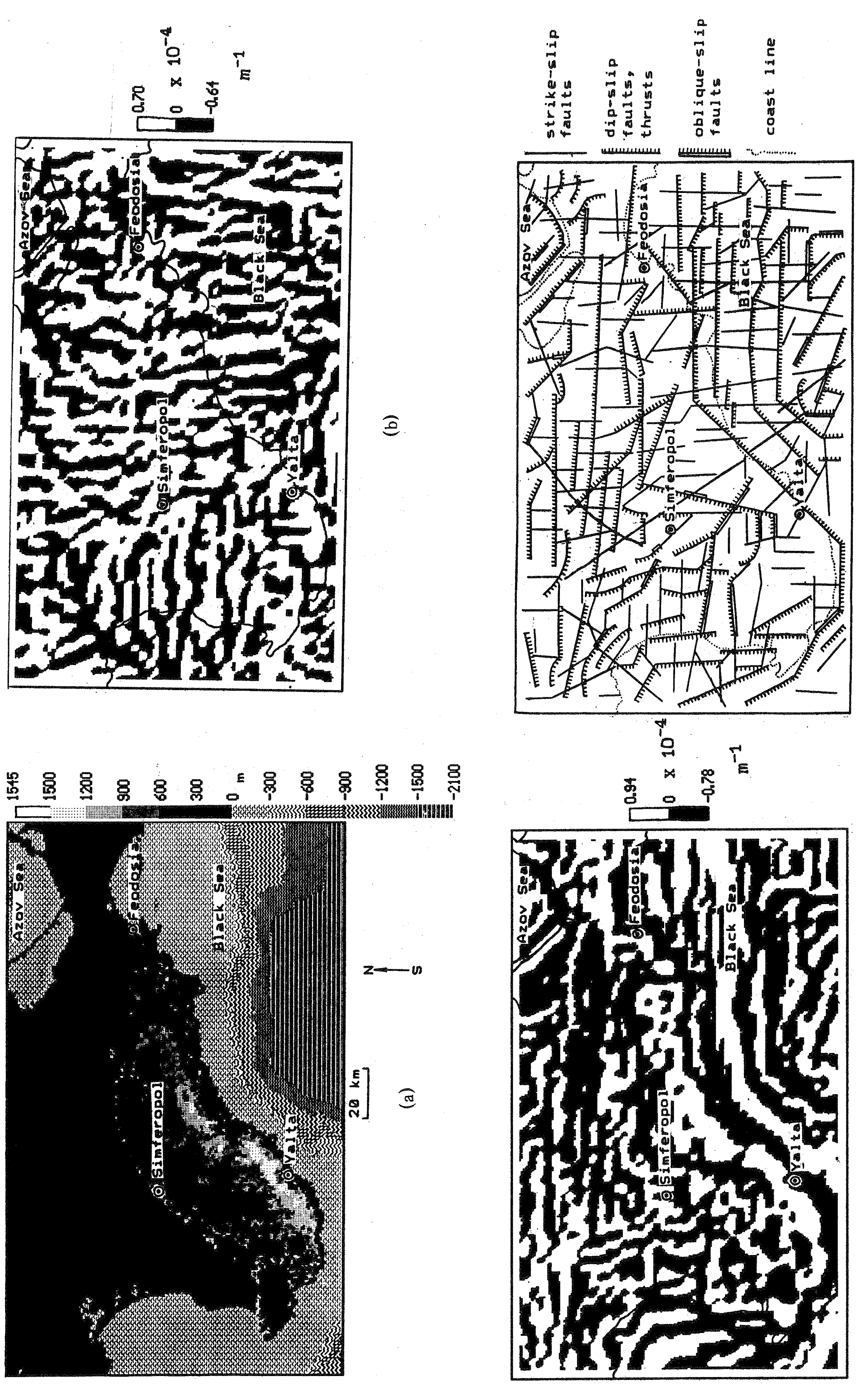

Fig. 2. The part of the Crimean Peninsula and the adjacent sea bottom: (a) - the elevation map, (b) - the Kh map, (c) - the Kv map, (d) - the map of morphologically classified faults revealed the Kh and Kv maps.

4. RESULTS AND DISCUSSION

4.1 The Abstract Area

Visual analysis of the maps obtained (Fig. 1) confirms that the theoretical basis of the method is mostly correct. After dip-slip faults modelling (Fig. 1 d) clear lineament passing strictly along fault axes is recorded on Kv map (Fig. 1 f). Some vertical motion traces are revealed by Kh mapping too (Fig. 1 e) but there are no lineament along fault axes.

After the strike-slip fault modelling (Fig. 1 g) only Kh mapping allows us to reveal a small lineament in the lower part of the map (Fig. 1 h). This lineament passes strictly along the dislocation axis. The Kv map does not contain lineaments (Fig. 1 i) although strike-slip fault traces are revealed which are a break of the valley and a displacement of its east part northward.

After the oblique-slip fault modelling (Fig. 1 j) the clear expressed lineament, the break of the valley and the displacement of its east part northward are revealed on the Kv map (Fig. 1 l). Vertical and horizontal motion traces are recorded by Kh mapping (Fig. 1 k) but there is no theoretically presumed lineament along the fault axis. This fact contradicts the theoretical basis of the method and, in principle, can be connected with drawbacks of the oblique-slip fault modelling. Besides, we may probably suppose a lesser "sensitivity" of Kh to horizontal tectonic motions (Fig. 1 h, k) as compared with Kv "sensitivity" to vertical movements (Fig. 1 f, l). However, real DEMs processing demonstrates that both Kh and Kv mapping allow us to reveal lineaments with equal "sensitivity" level (Florinsky, 1992). Probably, this may be a result of erosion influence which can increase topographic expression of faults, for instance, in forms of fault-line valleys or scarps.

After thrusts modelling (Fig. 1 m) clear lineaments passing along fault axes are revealed by Kv mapping (Fig. 1 o). Some overthrust traces are also recorded on Kh maps (Fig. 1 n) but there are no lineaments along fault axes.

After the gaping fault modelling (Fig. 1 p) the clear lineament is recorded on the Kh map (Fig. 1 q) as well as the lineament broken by the valley is revealed by Kv mapping (Fig. 1 r).

4.2 The Part of the Crimean Peninsula and the Adjacent Sea Bottom

Kh mapping allow us to reveal a) a complex of near-north oriented lineaments in the east and central parts of the study site, b) a complex of near-east oriented lineaments in the west part of the region, c) some near-north-east oriented linear structures in the north part of the study site, and d) some near-north-west oriented lineaments in the south part of the region (Fig. 2 b). Lineaments revealed by Kh mapping correspond to convergence areas (Kh negative values) and are connected with a valley network. A strong dependence of the Crimean valley network on the regional fault network was noted even by Muratov (1937). Lineaments recorded on the Kh map are mostly interpreted as strike-slip faults (Fig. 2 d).

Kv mapping allow us to reveal a) a complex of near-west oriented lineaments in the east and central part of the study site, b) a complex of near-north oriented lineaments mainly in the west part of the region, and c) some near-north-west oriented linear structures mostly in the south and the north part of the study site (Fig. 2 c). Lineaments revealed by Kv mapping correspond to relative deceleration areas (Kv negative values) and are connected with terraces. These lineaments are mainly interpreted as dip-slip faults and thrusts (Fig. 2 d).

Lineaments revealed on both Kh and Kv maps (Fig. 2 b, c) are interpreted as oblique-slip faults (Fig. 2 d).

The map of morphologically classified faults (Fig. 2 d) displays a complicated spatial distribution of faults. Dip-slip, thrust and strike-slip faults unite, as a rule, into complexes. The complex of near-north-striking strike-slip faults stretches through areas of different geological origins. Dip-slip faults stretch, as a rule, across strike-slip faults. There are some complicated faults which include dip-slip, strike-slip, thrust and oblique-slip offsets stretching along the same fault line one after another.

Obviously, the fault map obtained (Fig. 2 d) has a forecast and somewhat subjective nature. First, it is a result of slightly ambiguous drawing of fault lines. Second, a visual analysis of these maps may result in the loss of some lineaments. Third, this fault map corresponds only to the single matrix step 3000 m. Using a smaller matrix step we can obtain a map which will include more faults, while using a larger step we will obtain a map with fewer faults.

A visual comparative analysis of the fault map obtained (Fig. 2 d) and factual geological data made it apparent that a portion of revealed faults correlates with familiar ones. Another portion of revealed faults does not correlate with known structures. For the first time the complex of near-east-striking strike-slip faults is recognised in the west part of the region. Origin of these structures and their relationships with the regional tectonics is the subject of an individual study. It is very important that the most of the faults revealed and morphologically classified fit into the main regional fault groups.

However, familiar faults do not all were revealed. On the whole, this is the result of the use of the single matrix step. To recognise all the topographically expressed faults (and to range faults into trans-regional, regional and local groups) we have to use a set of Kh and Kv maps correspond to several matrix steps or extents of DEM low-pass filtering and smoothing (Florinsky, 1992).

5. CONCLUSIONS

For revealing and morphological recognition of topographically expressed faults it is necessary a) to calculate Kh and Kv by a DEM processing, b) to stratify Kh and Kv values into two levels with respect to the zero value, and c) to map Kh and Kv. Lineaments revealed on Kh maps indicate faults formed mostly by horizontal tectonic motions. Lineaments recognised by Kv mapping correspond to faults formed mainly by vertical motions and thrusting. Lineaments recorded on both Kh and Kv maps indicate, as a rule, oblique-slip and gaping faults.

The method was tested by processing the DEMs of the abstract area with modelled faults and the DEM of the part of the Crimean Peninsula and the adjacent sea bottom. For the abstract area the results obtained mostly correlate with the theoretical basis of the method. For the real area the comparative analysis of the results obtained and factual geological data demonstrates that the method actually works to identify individual faults in regions where both topography and tectonic structure are complicated.

The method developed is reproducible. It can improve information completeness and impartiality of laboratory geological works, contribute to their automation.

6. SELECTED BIBLIOGRAPHY

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