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II. Stress–Monitoring: the Modern Field of Regional Stresses in South–East Asia and the Oceania. Principles of Quasiplastic Deforming of Fractured Media

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Abstract. The main elements of an automatized method for stress–monitoring are presented together with the results of reconstruction of the field of modern regional stresses of the earth's crust in South–East Asia and the Oceania, based on seismological data on the mechanisms of earthquake foci. From the results of stress–monitoring the long–period component of the field of modern stresses in this megaregion revealed to exhibit a regularity in its space variations and to correspond to the concept of convective flows in the mantle, resulting in the movement of lithosphere plates in the Pacific Ocean subduction zone and of the India plate in the Pamir–Himalayan collision zone. The analysis of existing methods of reconstruction of tectonic stresses together with the algorithm underlying the stress–monitoring method has allowed to formulate the fundamental principles of the quasiplastic deformation of fractured media.

1. Introduction

In this work, the description is given of the procedures forming the core of the programming complex of stress–monitoring, i.e. of the reconstruction of tectonic stresses from seismological data on the mechanisms of earthquake foci, developed in the Tectonophysics Laboratory of JIPhE, RAS by Rebetsky Yu.L. and Gouschtenko O.I. Initially, the development of the programming complex was based on the kinematic postulates of quasiplastic deformation [Rebetsky, 1996], resulting from the dislocation theory of plasticity.

One of the principal procedures of the methods for reconstruction of parameters of both the stress tensor and the velocity tensor of quasiplastic deformations, a comprehensive review of which is given in ref. [Rebetsky, 1996], is the procedure of creating groups – samples of the structural–kinematic slip fault data (SFD) analysed together. Assuming that on the regional scale level analysed (the primary data are seismological data on mechanisms of the foci of earthquakes of magnitudes of $M_S > 4$) the mountain rock can be considered isotropic, we will further bear in mind the similarity between the tensors of tectonic stresses and of quasiplastic deformations due to displacement along faults [Rebetsky, 1996]. The question arises, as to which requirements every sample should obey, and to which extent it is arbitrary. Since each SFD has a space–time reference (here those SFD are meant which are obtained from seismological data on earthquake focal mechanisms), the issue is actually related to the method of identification of the macrovolume boundaries in space and in time, within which the averaged parameters of the corresponding tensors will actually be determined. Evidently, the identification criterion of these boundaries should be the requirement of homogeneity of the field of stresses and deformations within the limits of the macrovolume of averaging. In this connection, we should first of all introduce into the reconstruction algorithm a procedure for finding the boundaries of homogeneous macrovolumes, and only upon completion of the work of this procedure should we initiate the procedure itself for determining the parameters of the stress tensor. This problem is complicated by the known error in determining the initial SFD. Therefore, in the proposed reconstruction algorithm we pay special attention to solving the following problems:

1. the identification of homogeneous space–time macrovolumes, within the limits of which the SFD sample should be formed;

2. the development of regularizing algorithms, permitting to take into account the accuracy of the initial SFD and to enhance the stability of solutions.

In order to take into account the accuracy and the multiversion character of determining the mechanisms of earthquake foci within the algorithm of the stress–monitoring method, a graphical technique has been developed for calculation of the tensor of seismotectonic deformations, determining which, as demonstrated in ref. [Rebetsky, 1996], is equivalent, up to a constant factor, to determining the tensor of the average mechanism from a series of earthquakes with intersecting areas of elastic discharge.

2. Space–Time Boundaries of Uniform Macrovolumes

In the case of the reconstruction of effective stresses for a stress field, homogeneous in space and time, no problem arises in forming homogeneous samples. But when reconstructing natural tectonic stresses, we do not know in advance the boundaries of the macrovolume, within which the initial fault slip data correspond to an identical stress field not only in space, but in time, also. While in calculating paleo–stresses from geological data, the problem of identifying samples, that are homogeneous in space, is solved by geologists already at the stage of collecting the SFD, in the case of seismological data this problem requires solving in the course of reconstruction.

As a rule, the problem of finding boundaries of homogeneous macrovolumes is not considered in existing methods for calculating tensors of deformations and stresses. The process of completing the development of a sample depends on fixed boundaries, determined in advance, in time (the total time interval of observations) and in space (1–5 degrees by longitude and latitude). In some cases, the analysis is carried out of the character of convergence of a solution to some limit depending on the inclusion of each successive event into the sample. But when the tensor of interest is sought in the standard way, the influence on the solution of every successive event analysed decreases inversely with its ordinal number in the sample, and, consequently, such an analysis does not permit identifying the boundaries of homogeneous volumes.

In the proposed method of stress–monitoring for identifying homogeneous space–time macrovolumes the algorithm was applied of the right dihedra method [Angelier, 1984] already approved in ref. [Guschenko, 1990] for seismological SFD and which permitted not only to take into account the accuracy of initial seismological data on the focal mechanisms of earthquakes, but also their diversity. Since the basis of the right dihedra method is the identification, on a sphere of unit radius, of areas, where the exit points of axes of the principal stresses can be located, then in the following we shall term these areas of acceptable solutions (AAS) for the corresponding principal stresses. Successive summing of individual AAS, corresponding to σ_1 and σ_3, for some set of fractures, present in the homogeneous macrovolume, allows revealing regions of solutions satisfying the entire population of fractures under examination (cumulative AAS). Within the framework of this approach one may quite readily realize the method of estimation of the accuracy of the initial SFD by expanding the AAS of each earthquake by the appropriate value. The diversity of seismofocal mechanisms is taken into account as a similar manner. For every multiversion event the AAS of each axis of the principal stresses is the total AAS of all the versions.

For determination of the reference points of homogeneous macrovolumes, the coordinates of each of the earthquake foci analysed were identified with coordinates of the space–time center of the sample. In this case every successive event analysed has corresponding to it three parameters, characterizing its distance from the center. The sequence of the inclusion of events into the sample and of summing the individual AAS depended on two of its space parameters, corresponding to the respective lateral and vertical distances from the sample center, and, also, on one time parameter – the difference in time between the event to be included and the center of the sample. At the first stage of its formation the sample was increased in the negative direction of the variation of the parameter of the time interval relative to the sample center (the first events to be analysed were foreshocks relative to the sample center). An increase in the positive (aftershock) direction in time was performed only, when we failed to arrive at the criterion for completion of the reconstruction at the first stage of forming the sample. Such an approach allowed to speak about reconstruction of the tensor of tectonic stresses due to fault slip in the focus coinciding with the sample space–time center [Gouschtenko, 1995]. For fulfilment of the condition for intersection of the volumes of elastic discharge in calculating the tensor of seismotectonic deformations using the expression obtained in [Rebetsky, 1996]

$$\mathbf{S}_{ij} = K \sum_{\alpha=1}^{A} (n_i^\alpha s_j^\alpha + n_j^\alpha s_i^\alpha) \tag{1}$$

a test was performed to verify whether the sample space centre happened to be in the area of elastic discharge for every event added to the sample. In expression (1) s_i^α and n_i^α $(i = 1, 2, 3)$ are components of an observed unit vector of the movement s^α and of a unit vector n^α normal to the plane of the shear of earthquake number α. Here, the correlational relationship between a magnitude and the fault length was used, which had been established in ref. [Steinberg, 1983]. The area of the elastic discharge was taken to be proportional to the fault length, but different depending on the character of the seismic activity in the reconstruction region (this coefficient was taken to be large for regions of low seismicity).

Note that in forming the boundaries of homogeneous macrovolumes we need to solve the problem of the relationship not only of the time and space parameters, but also, owing to the presence of diverse scales (the Earth's crust is a sort of boundary layer in the tectonosphere of the Earth), of space distances in the lateral direction and into the depth. It is evident that this problem can only be solved experimentally. In the stress–monitoring algorithm, provision is made for variation of the maximum space–time boundaries of homogeneous macrovolumes (the initial space–time parameters of samples), on the base of which normalization was performed o` space–time parameters of earthquakes forming each sample. Further, each event was included intc the sample in accordance with its own radius–vector in this normalized three–dimensional space. When formation of the homogeneous sample was completed and the parameters of the stress tensor calculated, the final space–time parameters of the sample were determined including the lateral and vertical as well as time distances from its center, realized at a maximum. These parameters determine the real space–time volume, within which the sample formation was performed.

For realization of the identification of the boundaries of homogeneous macrovolumes on the basis of the right dihedra method, the upper hemisphere of a unit radius was divided into 604 subareas with intervals of 6 degrees between centers close to segments of the arc of the big circle. Summation of the individual AAS was performed for every axis of the algebraically maximum and minimum principal stresses separately on its own hemisphere. If a point (the subarea center) on the hemisphere did not fall into AAS of the event analysed, then the value corresponding to it was increased by one unit. The point was considered to belong to the combined AAS, if the value corresponding to it did not exceed a level given in advance of the possible noise (the noise level parameter is the ratio of the number of events, not satisfying the combined AAS, to the number of the sample events).

The necessary condition for including every analysed event into the sample consisted in that its own AAS had to contain at least the part of the AAS localized on the basis of preceding events (and not to contradict it). The first indication of the formation of a homogeneous sample being successfully completed was localization of the cumulative AAS to a value given in advance (the reconstruction completion parameter is the number of points determining the minimum AAS size).

The graphical approach, presented above, to the realization of restrictions of the right dihedra method permitted to carry out the major procedure of the stress–monitoring method – the AAS localization procedure, consisting of contraction of the AAS areas on a sphere of a unit radius in the course of accumulation of the number of events analysed in the sample. This procedure was the basis for sample formation. The procedure realized in the stress–monitoring method for localizing the cumulative AAS permitted not to lose any of the acceptable solutions from the reconstruction algorithm. For this reason, the localized AAS is, in many cases, a multiply connected area even at advanced stages. It should be mentioned that, as localization of the AAS proceeds, the sensitivity of the algorithm to the correspondence of events, newly involved in the analysis, to the condition of the deformation homogeneity increases. Precisely this feature of the right dihedra method has permitted to solve the problem of identifying homogeneous macrovolumes, which is an advantage of the stress–monitoring method developed in comparison with similar reconstruction methods of parameters of the stress tensor based on finding the extremum of the compatibility function and with methods for reconstructing parameters of the velocity tensor of the seismitectonic deformation.

3. Graphical Method of Determination of the Tensor of Seismotectonic Deformations

The procedure for determining parameters of the stress tensor was the next in importance after the procedure for identifying macrovolumes homogeneous in time in the stress–monitoring method. And parameters of the stress tensor were determined on the basis of the postulated isotropy of the geomedium properties via calculation of the velocity tensor of seismotectonic deformations (1).

It should be mentioned that the problem of reconstructing parameters of the velocity tensor of seismotectonic deformations requires the development of an automatized algorithm for the solution of a whole series of problems. The first is the problem of the stable determination of parameters of the S tensor on the base of SFD taking into account their accuracy. The second is the development of SFD samples, representative on the time interval, permitting to put the tensor of quasiplastic deformations into correspondence with the S tensor.

In the stress–monitoring method the algorithm for determining parameters of the tensor of seismotectonic deformations S was based on finding the trace of the Cauchy surface (the Cauchy surface of stresses [Cauchy,1827]) of the S tensor on a sphere of unit radius. In the given case, the determinant parameter of the Cauchy surface was taken to be equal to zero, which caused contraction of this surface toward the center of the ellipsoid of the S tensor. Plotting the trace of the Cauchy surface was performed by means of graphical summation of the nodal planes of individual mechanisms of events pertaining to the homogeneous sample, taking into account their accuracy and diversity. In the $X_1X_2X_3$ reference system with its center coinciding with the sample center, the equation of the Cauchy surface with the determinant parameter equal to zero has the form [Prager, 1963]

$$\sum_{i=1}^{3}\sum_{j=1}^{3}\mathbf{S}_{ij}X_iX_j=0 \qquad (2)$$

where S_{ij} are components of the tensor of seismotectonic deformations (1). Since the first invariant of the velocity tensor of seismotectonic deformations is zero, the Cauchy surfaces are two hyperboloids, oriented symmetrically with respect to the principal axes of the S tensor

$$\sum_{i=1}^{3}\mathbf{S}_{ii}X_i=0 \qquad (3)$$

Here X_i are coordinates in the reference system, connected with the principal axes of the S tensor. Note that the projection onto the plane normal to the axis of the Cauchy hyperboloid of the trace of its intersection with the sphere is an ellipse. So, in intersecting the unit sphere the Cauchy hyperboloids form a symmetric pair of nonplanar ellipses, and the symmetry axes of this pair coincide with the principal axes of the tensor of seismotectonic deformations. Using (3), the equation for the surface of the sphere, and the relations expressing the main components of the tensor of seismotectonic deformations via the coefficient of the sort of deformed state and the value of the maximum displacement (expressions similar to those presented in ref. [Rebetsky, 1996] for deviatory stresses (4, 5)), we can obtain

$$X_1^2+(1+\mu_\varepsilon)/2X_2^2=(3+\mu_\varepsilon)/6 \qquad (4)$$

where μ_ε is the coefficient determining the sort of the ellipsoid of the tensor of seismotectonic deformations (the coefficient of the kind of deformed state). Expression (4), together with the above described symmetry of the Cauchy hyperboloid with respect to the principal axes of the S tensor, allows to determine the parameters of the tensor of seismotectonic deformations from the form of its trace on the sphere.

Determination of the trace of the Cauchy surface was performed graphically on a sphere of unit radius and actually consisted in finding the mean nodal surface averaged over all the events in the sample. Within such an approach, to be distinguished from direct summation of the tensors, it turns out to be possible to take into account, in a quite simple and effective manner, the accuracy in determining the nodal planes. This is achieved by introducing zones of the probable locations of nodal planes for each event, including the multiversion ones.

At each step in the calculation, after testing a successive event for the fulfillment of the necessary condition for homogeneity of the sample, a check was performed of whether the axes of the tensor of seismotectonic deformations, determined graphically, happened to be within the localized cumulative AAS or not. A positive answer was the sufficient condition for including the event analysed into the sample.

Successful completion of the formation of a homogeneous sample and of reconstruction of the stress tensor was indicated by localization of the AAS area to the value given in advance together with fulfilment of the conditions of smoothness of the graphical presentation of the trace of the Cauchy surface on the sphere (the smoothness parameter of the solution is the degree of symmetry of the tensor of seismotectonic deformations and the closeness in form of the trace projection to the form of an ellipse). The fulfilment of the necessary and sufficient conditions during sample formation provides for fulfilment of the condition of space–time homogeneity of the parameters of the stress tensor in the macrovolume investigated. Together with the indication of successful completion of the sample formation they signify fulfilment of the condition of representativeness and completeness of the earthquake mechanisms chosen to be included in the sample, which permits us to claim that the tensor of seismotectonic deformations is similar to the tensor of quasiplastic deformations. After successful completion of the sample formation, the orientation of the axes of the principal stresses was set to coincide with the orientation of the principal of the tensor of seismotectonic deformations, and the Lode–Nadai coefficient was determined graphically from the form of the trace on the sphere of the Cauchy elliptical hyperboloid.

In ref. [Gouschtenko, 1990] the right dihedra method was also applied in sample formation. But the axes of the principal were determined by means of AAS localization without relating them to the orientation of the axes of the tensor of seismotectonic deformations. Since the initial algorithm of the stress–monitoring method was based on a concept similar to the one presented in ref. [Gouschtenko, 1990], we compared the results of both approaches. It was found that application of the algorithm presented in this work resulted in a large number of determinations involving multiply connected AAS areas, which corresponded to the solution not being unique. Another important conclusion drawn from the comparison was that this algorithm gave rise to situations being encountered of unstable determination of the axis index. This instability resulted in errors in the determination of indexes of the axes of the principal stresses for states approaching uniaxial compression or uniaxial tension.

It should be mentioned that for reconstruction of the Tibet modern stress field on the basis of seismological SFD an algorithm was used in ref. [Carey–Gailhardis, Mercier, 1987], which combined the right dihedra method and the method of finding the extremum of the compatibility function. In doing so the right dihedra method was used at the first step, and areas of the possible orientation of axes of the principal stresses were determined. Next, the one of the two nodal planes was established, which fulfilled the requirement that the Lode–Nadai coefficient be positive, and which was taken as the fault surface. Then the algorithm was used of finding parameters of the tensor of deviatory stresses by the method of analysis of the "homogeneity function" extremum in a form close to expression (3) presented in ref. [Rebetsky, 1996]. Such an approach permitted to solve a series of problems related to nonuniqueness both at the stage of introduction of the initial SFD (multiversion mechanisns) and in the course of finding the maximum of the compatibility function (identification of the slip surface).

To conclude this section we must draw attention to the possibility, inherent in the stress–monitoring algorithm, of determining the tensor of effective stresses for different time scales, which constitutes its monitoring peculiarity. This possibility is connected with variation of the relationship between parameters determining space–time boundaries of homogeneous samples. Setting the boundary for the sample by the time scale to be the greatest possible, specified actually by all the instrumental period of observations with the minimal necessary space boundary (the radius of the lateral distance and the depth range), we obtain, as a result of the reconstruction, data on the character of space variations of the stress tensor in the region investigated, averaged over all the observation period – the long–period component of the stress tensor. Taking as the sample boundary by the time scale the minimal possible one, specified on the basis of an analysis of the seismicity activation period, with the greatest possible space boundary, connected actually with the character of the space inhomogeneity of the stress field in the long–period component, we obtain the data on the short–period component of the stress tensor. In the last case the evident consequence is the necessity of plotting series of maps for different time ranges.

4. Results of Stress–Monitoring

The stress–monitoring algorithm developed was tested for the seismological data bank for more than 9000 focal mechanisms of crustal earthquakes of magnitudes $M_S > 4$ in South–East Asia and the Oceania that occurred between 1924 and 1990. All the data were subjected to preliminary tests and adjusted, which allowed us to correct a great number of errors both of systematic and irregular character. The peculiarity of the bank of mechanisms developed by us lies in its diversity, i.e. each earthquake can have corresponding to it several versions of mechanisms, determined either by different authors or by a sole author [Wickens, Hodgson, 1962]. The goal of the present stress–monitoring was to obtain data relevant to the long–period component of the tensor of modern stresses acting in the earth's crust in the megaregion investigated and to form, on their basis, graphical concepts – maps, indicating regularities in its space variations. Therefore, the parameters of the stress–monitoring complex were set to be the following: the initial space–time boundaries of the homogeneous sample were on the average more than 50 years in time and 200 km in lateral distance, the length range was 40 km (for areas of active seismicity the lateral distance was 100 km, the length range was 20 km, for areas of low seismicity the lateral distance was 300 km., the length range was 40 km.). The level of reliable noise was set at 10% of the number of sample events, the size of the cumulative AAS for completion of the reconstruction was 150 points, the precision in the determination of mechanisms was 15 degrees,the indicator of symmetry and the degree of smoothness of the trace of the Cauchy hyperboloid was 80%. After processing by the stress–monitoring programs, the parameters of the tensor of deviatory stresses were obtained at the hypocenters of more than 6000 earthquakes, the data on which were presented in

[Gouschtenko et al., 1993; Gouschtenko, Rebetsky, 1994] together with the results of a very preliminary analysis.

Since one of parameters of the reconstructed tensor is the orientation of the axes of the principal stresses, we can map the projections of the trajectories of axes of the principal stresses from the results of calculations. The trajectories of axes of the principal stresses are curves, tangents at each point of which are parallel to an axis of the corresponding principalstress acting at the same point. We recall that, by definition, trajectories of the principal stresses are continuous curves, which can have break points related to ruptures of continuity and with sites of reindexation. An exception, here, are areas near isotropic points [Kachanov, 1969]. At reindexation sites, breaks of a trajectory are due to the definition adopted in mechanics: $\sigma_1 > \sigma_2 > \sigma_3$.

Plotting maps of the projections of trajectories is connected with a certain problem caused by the necessity of interrupting a trajectory, when it comes out onto boundary surfaces of the volume, within the limits of which the reconstrustion is carried out. This happens, for example, in the present work, when the trajectory comes out onto the spherical surfaces restricting the conventional crust, i.e. the surface layer of the lithosphere of thickness 40 km. Here, for conservation of the continuity in drawing the projections of trajectories on the map, we must draw a new trajectory from the bottom of the conventional crust immediately under the outcome point of the trajectory onto the day surface and vice versa. Thus, breaks of the projections of trajectories appear on the map, which are not related to reindexation or to violation of the geomedium continuity.

There also exist other possibilities for construction of the fields of trajectories reflecting the character of the space variation of dynamic parameters of the deformational process. Thus, for example, it is possible to construct maps of trajectories of projections of axes of the principal stresses – curves, the tangent at each point of which gives the orientation at this point of the projection of an axis of the associated principal stress. In that case, only those data are used in the mapping that are relevant to the azimuthal orientation of axes of the principal stresses. This method permits constructing the trajectories of projections in a continuous manner and is readily subjected to program algorithmization. But it should be mentioned that, like in the course of construction of the trajectories of axes of the principal stresses, the construction of the trajectories of their projections becomes unstable in areas where associated axes are subvertical. Owing to this circumstance, in such areas it is necessary to break drawing both types of trajectories. Note that both these methods yield close results, when axes of subhorizontal orientation are constructed.

There also exists a third method of construction of trajectories indicating the space variability of dynamical characteristics. This is the construction of trajectories of the main axes of an ellipse, resulting from the intersection of the stress ellipsoid and the plane parallel to the day surface at the given point. The last method permits to determine the orientation of horizontal maximal tension and compression stresses acting in the earth's crust (pseudo–principal stresses). In such a method the disadvantages of the two methods mentioned above are absent in the construction. The trajectories of both families (of the minor and major semi–axes of the ellipse) are constructed stably and can have breaks related only to reindexation of the pseudo–principal stresses and to already existing breaks.

Speaking about the trajectories of axes of the principal stresses, we note that utilization of the isotropy postulate allows the following kinematic interpretation. Since each family of trajectories of the principal stresses forms surfaces, the angles of intersections of which do not undergo distortions during the deformation process, it follows that each family of trajectories forms a surface, which is the locus of points with one and the same component of movements in the direction of the normal to this surface. Thus, an analysis of the character of the trajectories of the principal stresses allows to formulate quite effectively the boundary conditions for the regional tectonophysical modelling in a kinematic form.

The analysis of the results obtained reveal the fundamental features of the reconstructed field of modern tectonic stresses in South–East Asia and the Oceania to be the following:

1. The variation of orientations of axes of the principal stresses and of the trajectories of their projections has a regular character with a high level of smoothness (Fig. 1) (the trajectories of the projections of axes of the principal stresses were drawn where the angles of incidence of axes did not exceed 60 degrees). Practically all the areas with sharp variations in the orientation of the principal stresses are confined to the extreme areas of large regional ruptures on continents and to nodes of conjugation of the oceanic grooves or to areas of reduced strength (Pamir). Zones occur of the index of the axis of the principal stresses varying along the direction of their trajectories, which can be related both to the presence of plutonic crust faults and to reindexation of the principal stresses for values of the Lode–Nadai coefficient close to plus and minus one (in Fig. 2 these areas are indicated by diagonal hatching and by speckles, respectively).

2. In seismofocal areas near the oceanic grooves it is typical for the orientation of projections of axes of the principal compression and tension deviatory stresses to be normal to their trend with the plunge of axes of the principal compressive stresses under the oceanic lithosphere plate, and of the principal tension stresses – under the continent. Axes of the intermediate deviatory stress, as a rule, are parallel to the trend of grooves or are at a minor angle to it. Variations should be separately mentioned of the incidence of axes of the principal compressing stresses across the trend of the Philippine islands with a subhorizontal position in the axial region. Here, across the trend of the arc there also occurs a change of index for the stress of subhorizontal orientation. At the eastern part of the island arc this index corresponds to the intermediate stress, and at the western part – to the maximum tension stress (Fig. 1).

3. In the join zone of the India and Eurasia plates the axes of the principal compressing stresses are also directed along the normal to the trend of the Pamir–Himalaya seismoactive area with the direction of incidence under the India plate. Note the characteristic radial subhorizontal distribution of the directions of axes of this stress for the vast areas of Central Asia and China. Here, the directions of axes of two other principal stresses form the radial–concentric field of the trajectories of the principal stresses (Fig. 1). The regularities of the space orientation of the horizontal compression and tension forces are most clearly revealed in Fig. 3, in which the principal axes of the ellipse are constructed in the horizontal section of the deformation ellipsoid. On the basis of the possibility described above of the kinematic interpretation of trajectories of the principal stresses the conclusion can be made that the India plate overthrusts onto the Eurasia plate in the north–eastern direction (the deviation from the direction to the North is within the limits of 30–40 degrees), experiencing no turn in the process.

4. The known areas of grooves (the India ocean and Baikal continental) have corresponding to them the direction of axes of the principal tension stresses normal to their trend, and the subvertical direction of the principal compressive stresses (Fig. 1). The coefficient of the type of

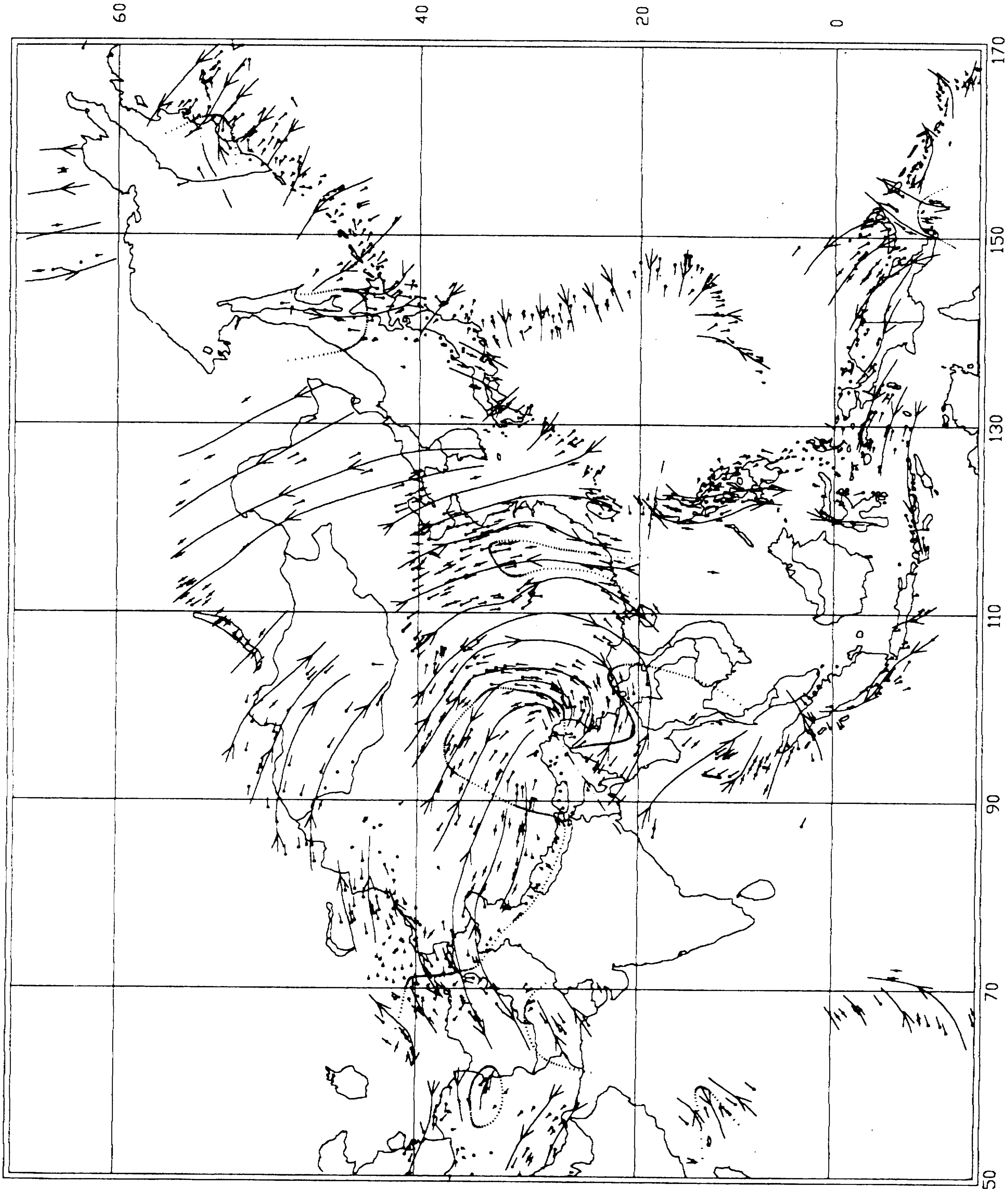

Fig.1a

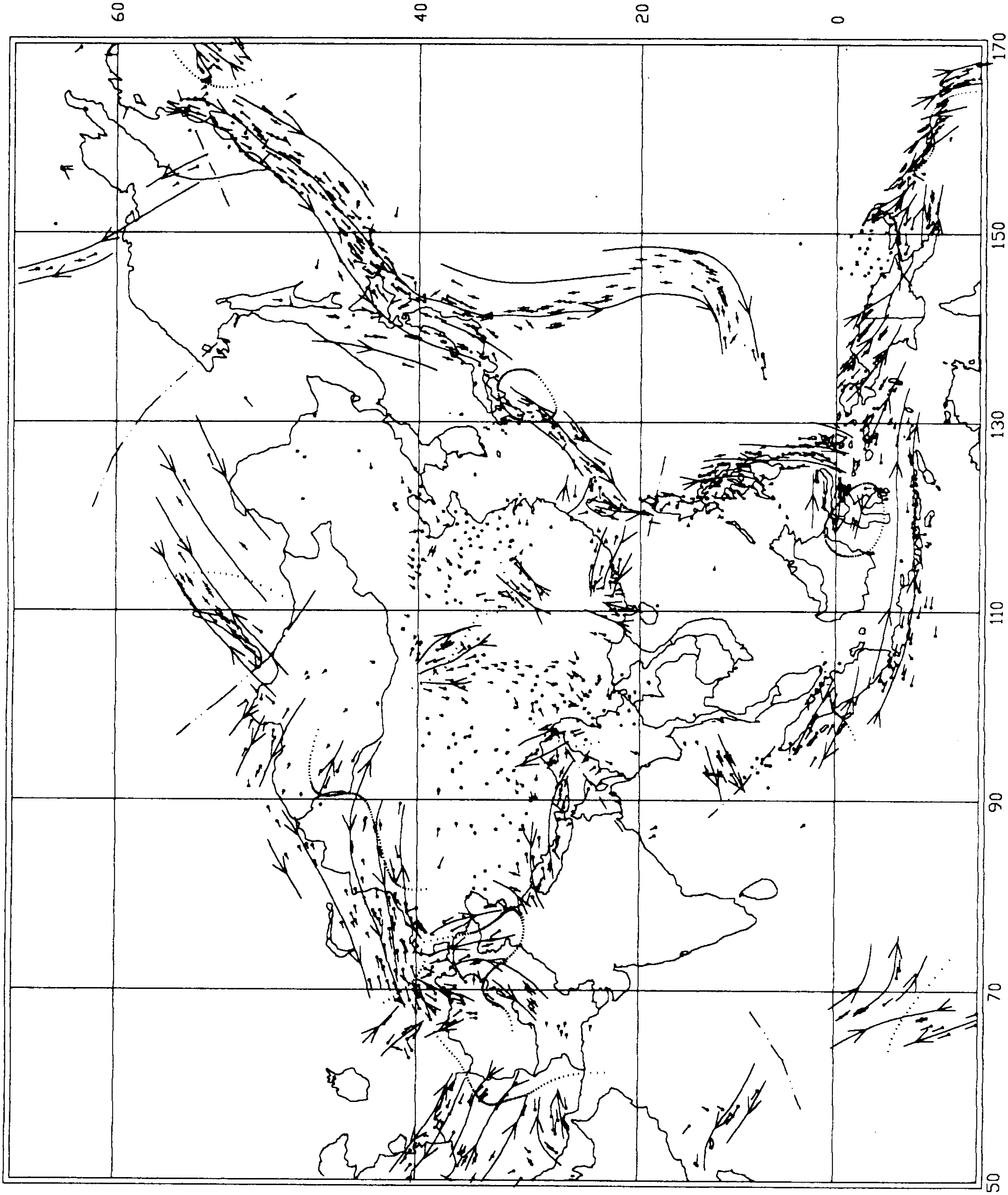

Fig. 1b

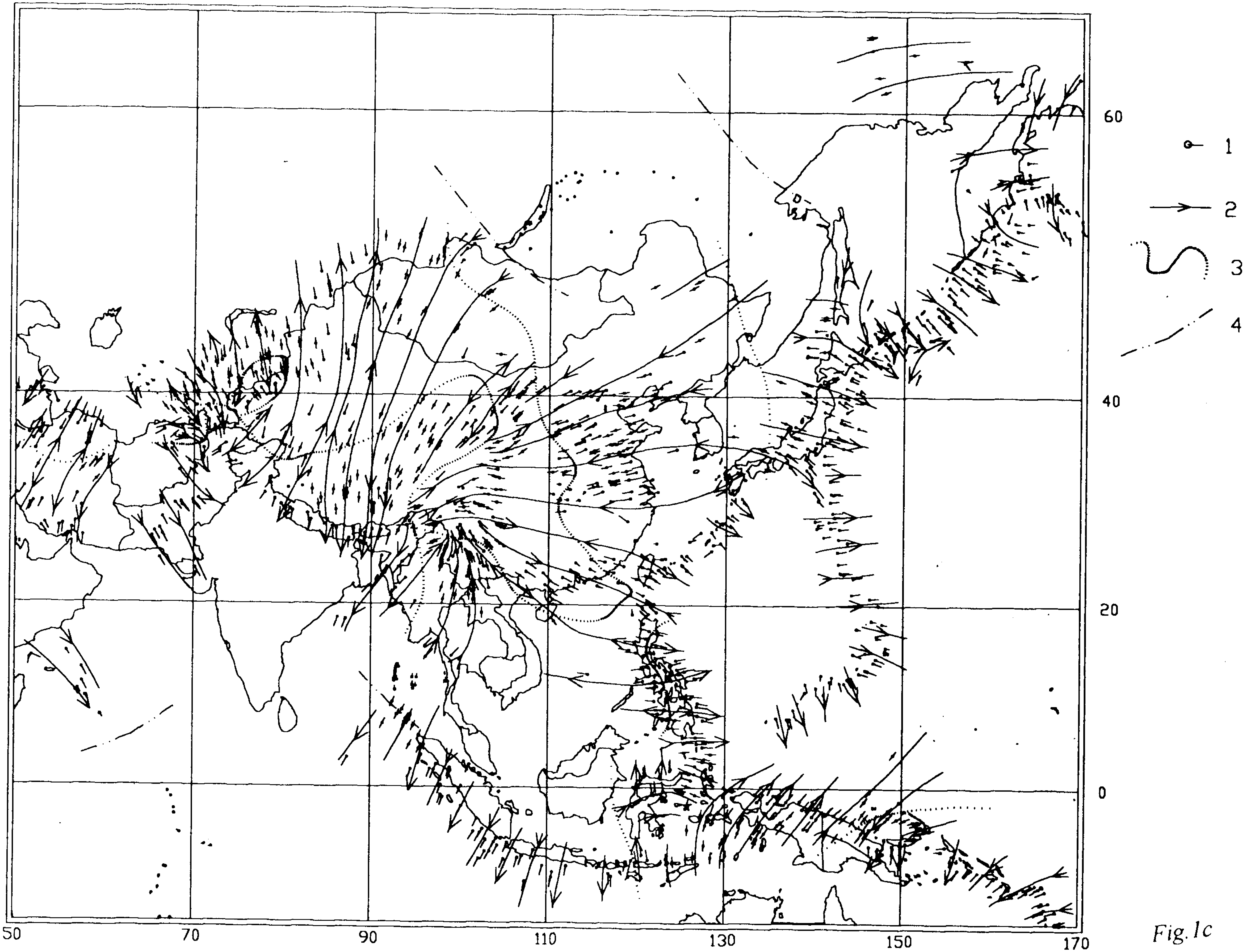

Fig.1. Orientation of projections of the incidence axes of the principal stresses and their trajectories: a) —σ_1, b) —σ_2, c) —σ_3.

1 – projections of the incidence axes, 2 – trajectories of the principal stress projections, 3 – boundaries, near which the variation occurs of the direction of dipping of axes of the principal stresses, 4 – boundaries, near which the sharp variation occurs of the orientation of axes of the principal stresses.

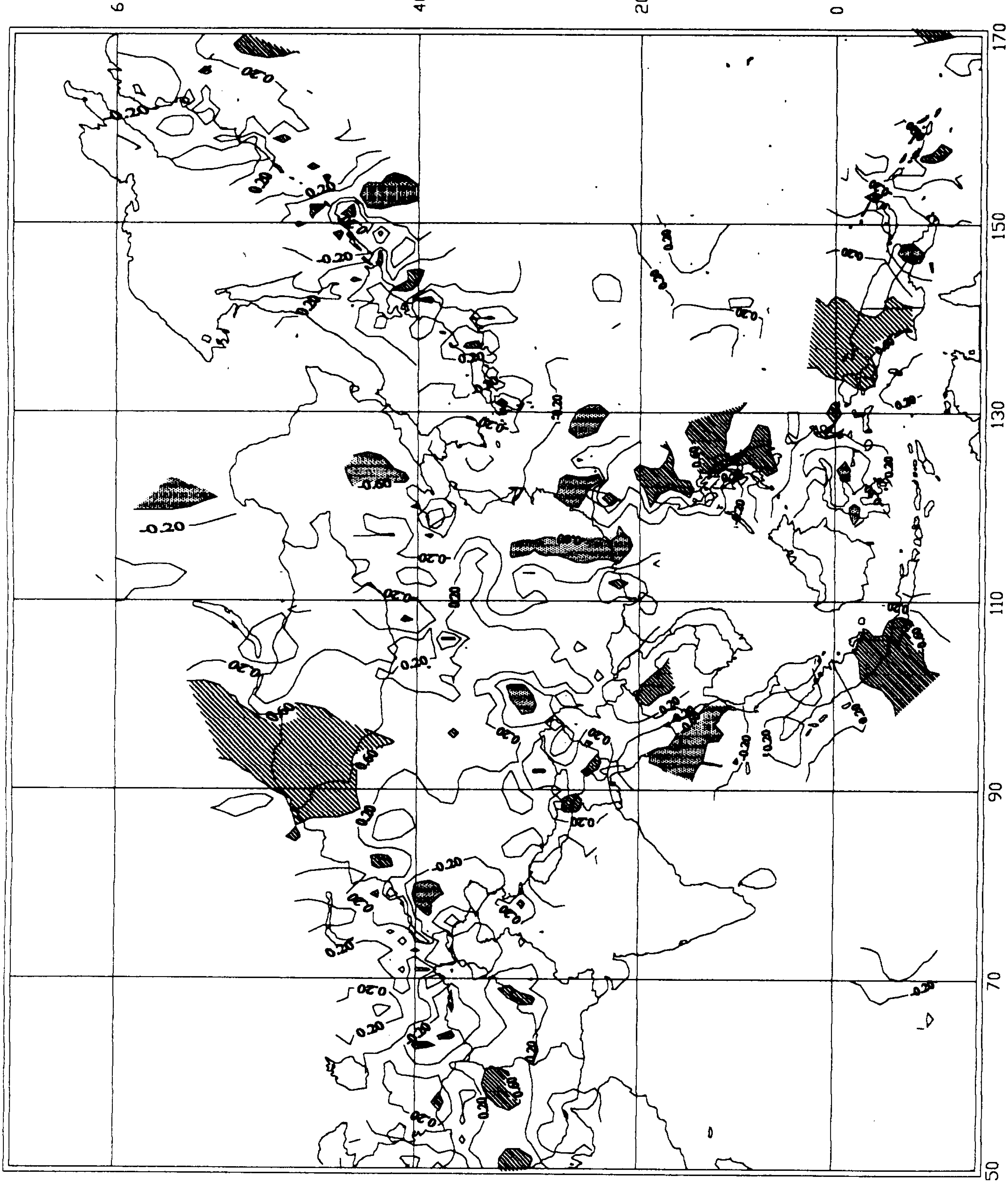

Fig.2. Isolines of the Lode–Nadai coefficient.
1 – areas of $\mu_\sigma > 0.60$; 2 – areas of $\mu_\sigma < -0.60$.

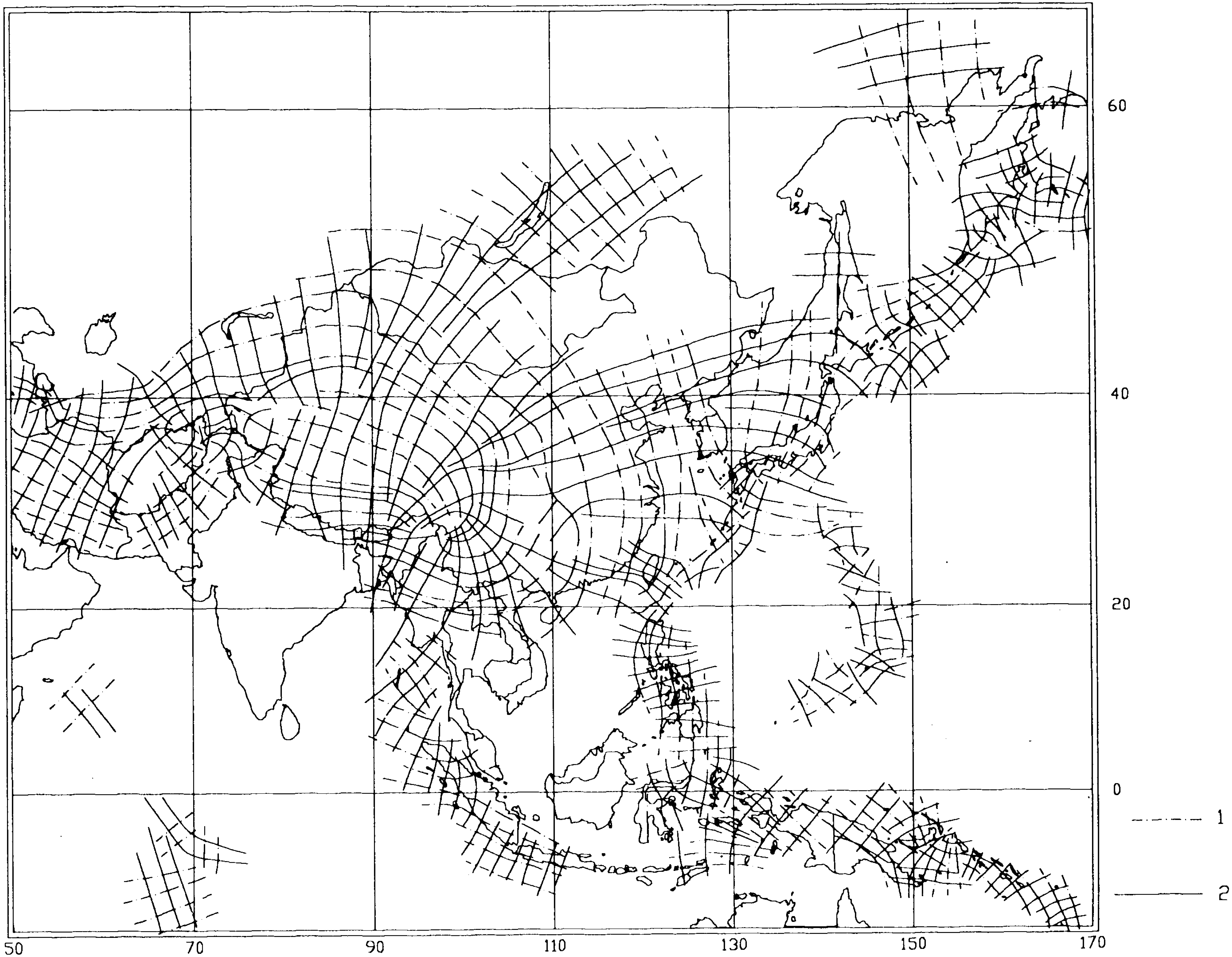

Fig.3. Trajectories of the minor and major semiaxes of the ellipse in the horizontal crosssection of the stress ellipsoid (pseudo–principal stresses).

1 – the deviatory stress of tension, 2 – the deviatory stress of compression.

stress state μ_σ close to zero is characteristic for these areas – a pure strike–slip fault (Fig. 2).

5. On the basis of the data on the orientation of axes of the principal stresses (Fig. 1) and on the values of the Lode–Nodai coefficient (Fig. 2) the directions of action were calculated of the shear stresses at the bottom of horizontal areas (Fig. 4). They demonstrated that the underthrust forces at the bottom of oceanic lithosphere plates are oriented from the ocean toward the continent, which confirms the legitimacy of examining the deformation processes in the areas of oceanic grooves from the standpoint of plate tectonics, explaining them by convective flows in the upper mantle. The orientation of these underthrust forces in the narrow zone of the Pamir–Himalaya collision area is also consistent with the concept of active subcrustal flows, causing the submeridional movement of the India plate. The absence of any stable picture of directions of action of the shear stresses at the bottom of the South–Eastern Asia continental lithosphere within the limits of its central and eastern parts is characteristic here. This can be explained by the subhorizontal pressure in the lithosphere plate, transmitted from the zones of collision and subduction, serving as the external active deforming force, instead of the convective flows in the mantle.

6. On the basis of data on the orientation of axes of the principal stresses the map was constructed of the types of stress state (Fig. 5). Here, following ref. [Sherman, Dneprovsky, 1989], a subdivision into six types of fields was used. Such a subdivision was carried out by analysing the relative position of the vector toward the zenith within the system of three vectors of the uprising of axes of the principal stresses (the scheme of Fig. 5). In this map, a vast area stands out of a shear stress state and of other types close to it in the continental China, of a fault stress state in the areas of grooves, and of an upthrust state in the oceanic areas of subductions and of the Pamir–Himalaya collision. This zoning actually reflects the character of earthquake focal mechanisms, precisely on the basis of which the reconstruction was performed. The difference consists in a more clear identification of boundaries for the different types of stress state based on data relevant to the fields of the reconstructed stresses.

7. The data on the orientation of axes of the principal stresses make it possible to construct planes of action of the maximum tangent stresses, the comparison of which with mapped significant geological faults allows to carry out zoning in accordance with their activity at the present stage. The maps for the trajectories of vectors of the strike of the planes of maximum shear stresses with the respective and left–shearing components of displacements are presented in Fig. 6a, b. Since, for the planes of a subhorizontal position, the unstable orientation was observed of the vectors of the strike, the trajectories on the maps are shown for the subvertical planes (the angle between the plane and the horizon exceeded 30 degrees). On these maps, the kinematic type of the faults (fault, shear–fault, inversion fault) is shown by a special mark along each of the trajectories from the side of the fall of the plane. The characteristic element of the maps represented is a change of the kinematic type of fault–formation along extended trajectories.

The data on the parameters of the tensor of modern stresses obtained in the form of maps can be compared with known reconstructions of tectonic stresses for this region. Thus, for example, comparison with data presented in ref. [Zhonghuai et al., 1992], in which the trajectories of the principal stresses are constructed for the China territory, demonstrates good convergence of the results of both reconstructions. Here, it should be mentioned that the sizes of the macrovolumes of averaging were different and were selected on the basis of an analysis of the intensity and character

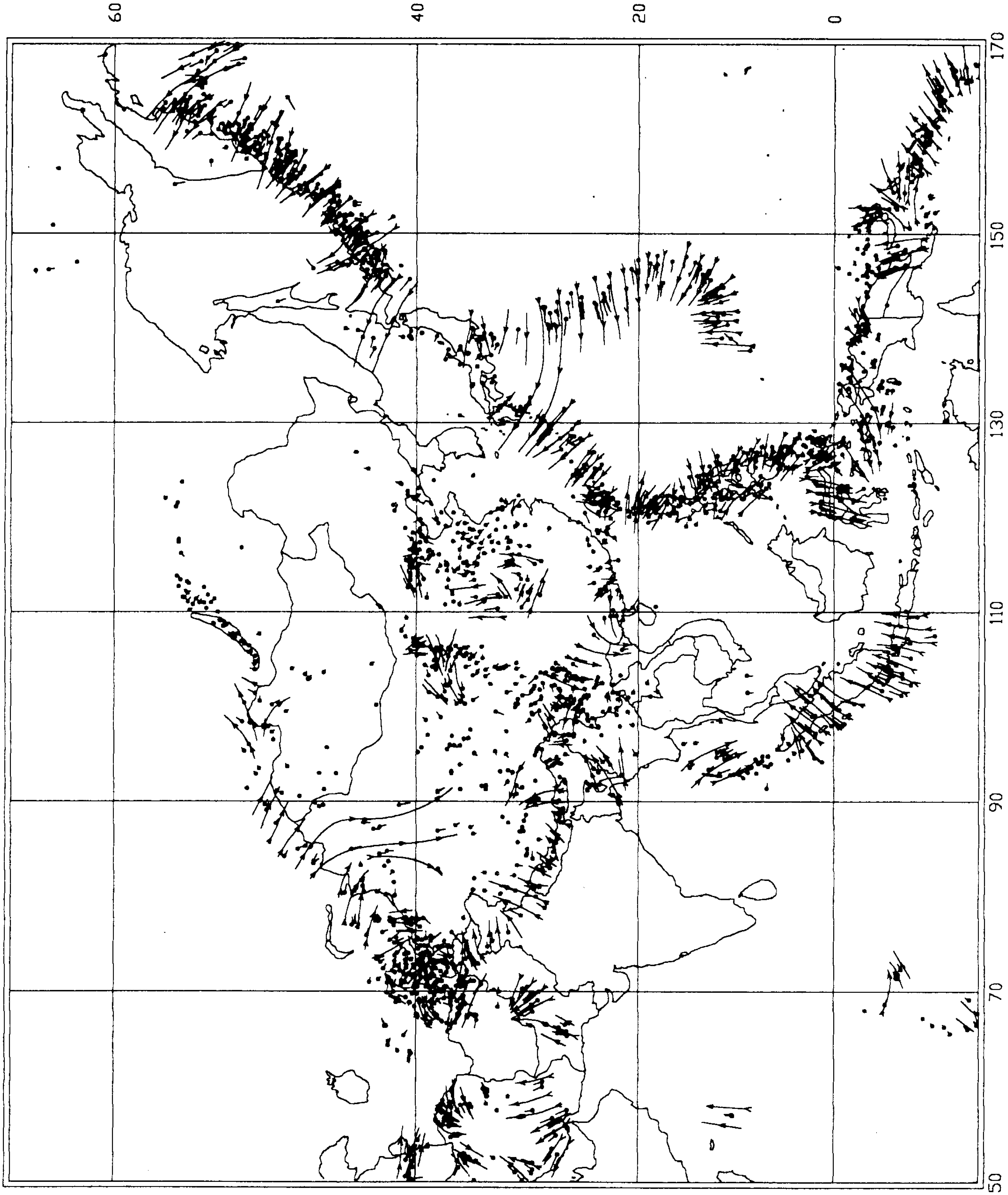

Fig. 4. Orientation of axes of shear stresses at the bottoms of horizontal planes and their trajectories.

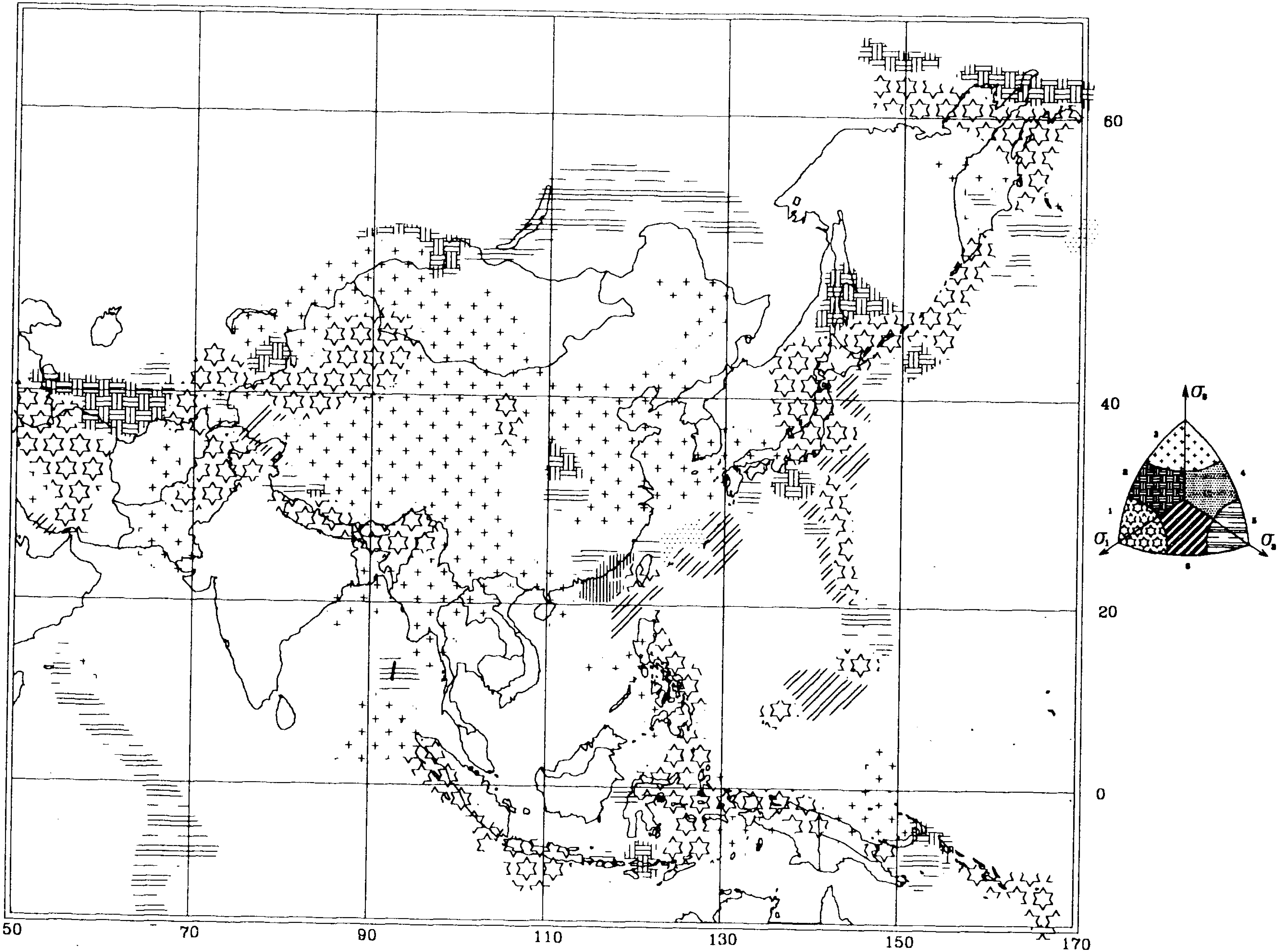

Fig.5. The map of six types of the stress state.

1 – inversion fault, 2 – inversion fault–shear fault, 3 – shear fault, 4 – strike–slip fault, 5 – fault, 6 – upcut.

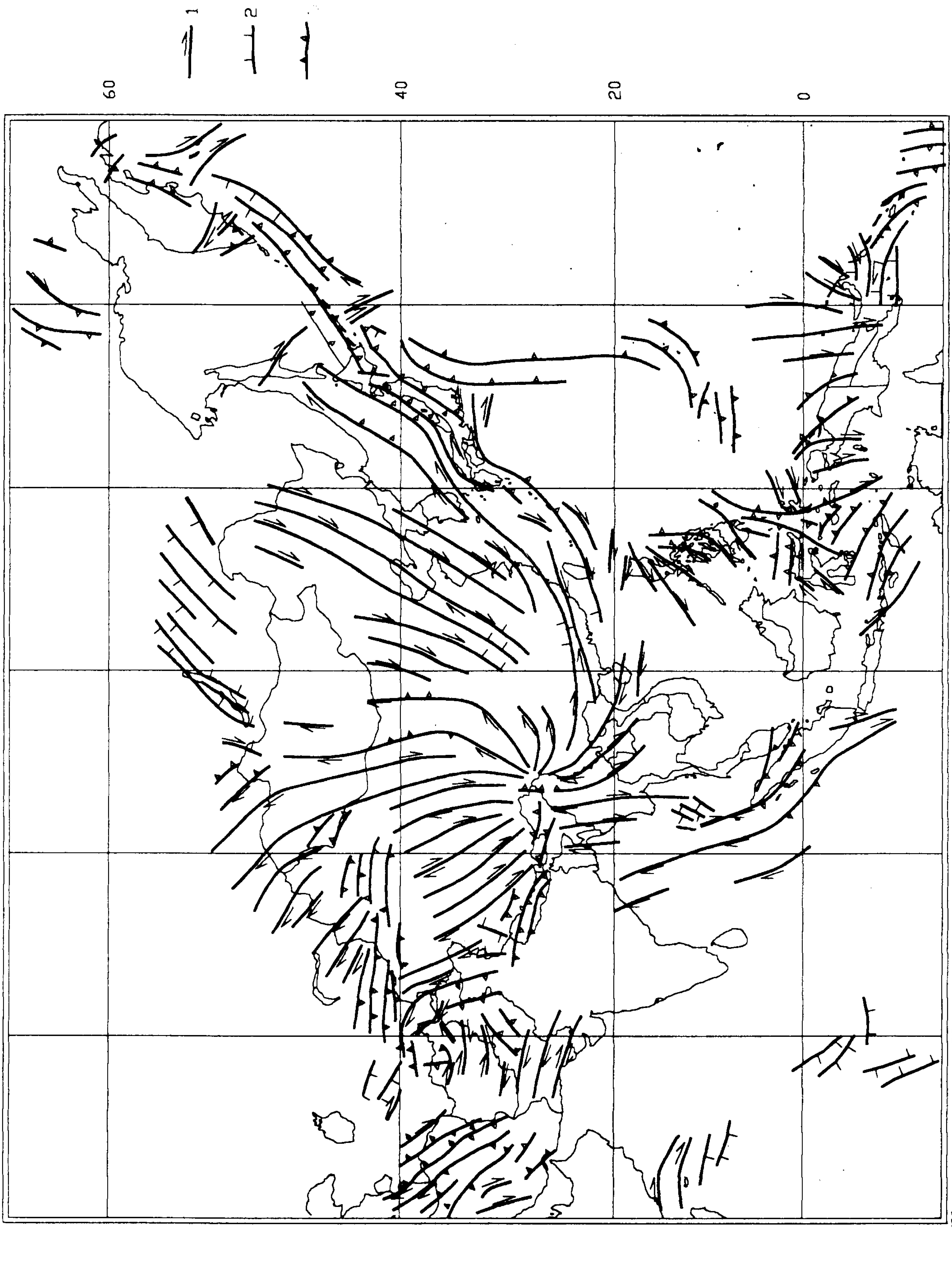

Fig.6a

Fig.6b

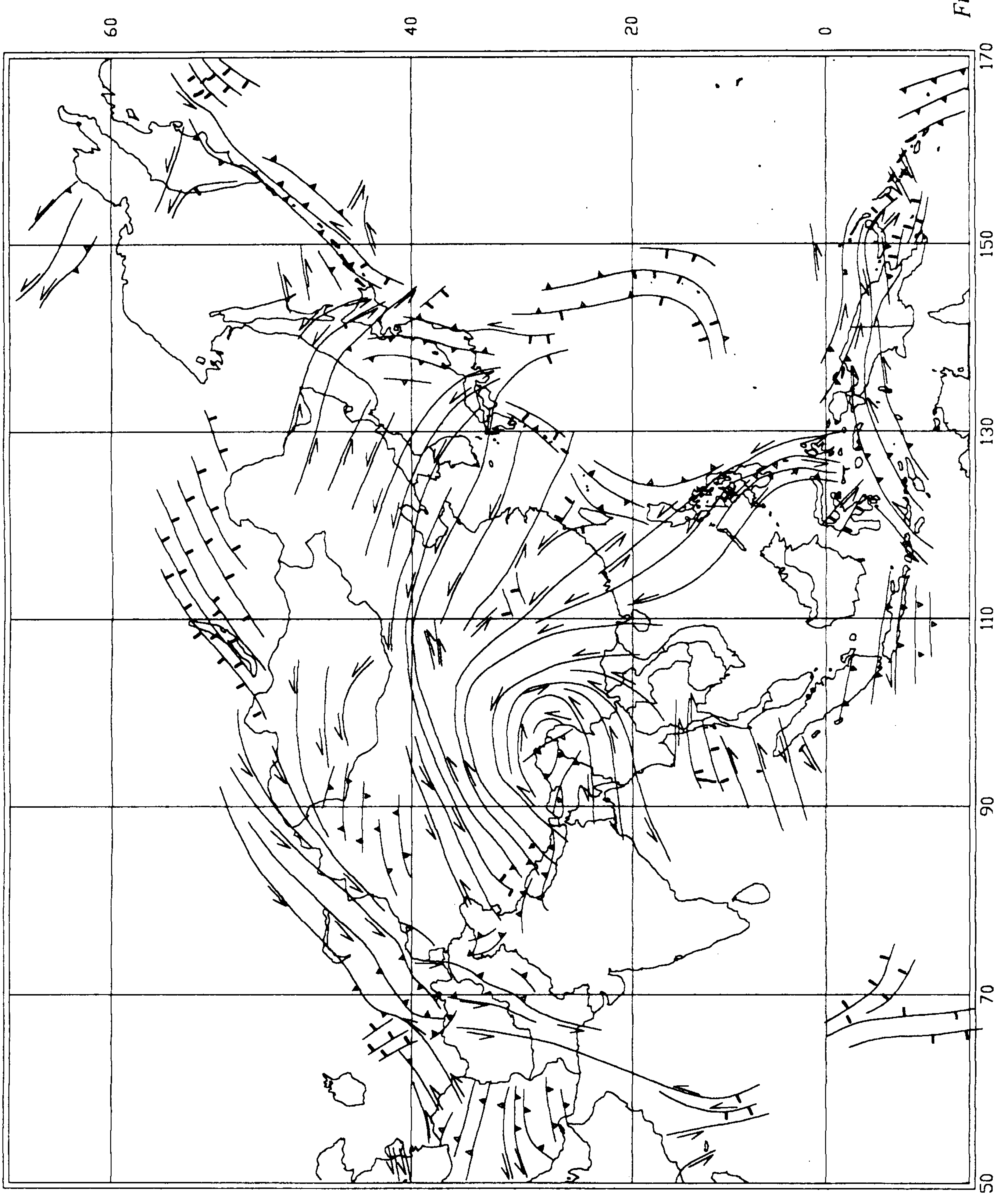

Fig.6. Trajectories of trends of subvertical planes of action of maximal tangent stresses: with a right-shearing (a) and left-shearing (b) displacement components.

1 – shear faults, 2 – faults, 3 – inversion fault.

of the seismicity, while the actual reconstruction method used in ref. [Petrov et al., 1994] was close to the graphical method for determining the tensor of the mean mechanism via the seismological SFD. In the work mentioned reconstruction was performed of the modern stress field for the same region applying the right dihedra method approved in ref. [Gouschtenko et al., 1990] for data on earthquake focal mechanisms. But the stress field obtained is considerably more complex in form, which is manifested in the presence of a great number of faults of smoothness in the orientations of the trajectories of projections of the principal axes of the tensor. From our point of view, this feature is related to the instability mentioned above of the algorithm applied. In ref. [Zobak, 1992] there are presented, also, data on the stress field of the region under investigation, but the instability observed of determinations, here, is even more considerable.

5. On the Method of Reconstruction of the Tectonic Stress Tensor

Analysis of the results obtained has demonstrated their being quite consistent with basic concepts of the character of deformation processes in the tectonically active areas of the megaregion investigated. In particular, they correlate with geological observations and simulations of deformations for Chinese territory, presented in ref. [Viotte, Daignieres, 1982]. It should be specially mentioned that in the megaregion under investigation practically all the main deformation mechanisms are present: grooves, both oceanic (the India groove), and the continental (the Baical groove), subduction zones (the Kurily–Kamchatka, Philippine, Javanese, and Marian systems of grooves), and collision areas (India–Himalaya), as well as areas of continental shear–faults (the Median–China area of shear–faults). In all these areas, with significantly different regimes and characters of seismic processes, the stress–monitoring method has yielded good results. This, primarily indicates that the algorithms underlying it reflect the physical rules of the geomedium deformation quite accurately.

At the same time, it should be recalled that the kinematic postulates, precisely on the basis of which the stress–monitoring algorithm was developed [Rebetsky, 1996], impose relatively severe restrictions on the character of the deforming process and on the properties of the geomedium. Indeed, one of the postulates actually claims the tensor of macrostresses to remain invariable in the process of realization of quasiplastic deformations over the set of differently oriented faults. In another postulate, it is assumed that, if the loading, external with respect to the macrovolume, is the same, then the displacement along each faults in a macrovolume involving numerous such faults is identical to the displacements along faults oriented in the same way, but existed singly in each of a multitude of macrovolumes (a fracture with a loading at infinity). As a matter of fact, it is quite evident that every microact of the conversion of a part of the elastic deformation into residual deformation due to the displacement along the fault results in a change in the stress state in the vicinity of this fault. And, as it has been already mentioned above, the size of the area of this change depends on the dimension of the fault, and the value of stresses discharged depends on the slip direction. Note that in ref. [Bott, 1959], in relating the slip directions along the shear plane to the tensor of stresses acting before its apperance, the stress state remaining invariable after destruction was not considered.

The question arises as to how to explain the fact that a stable and quite reliable, from a tectonic point of view, result was obtained during the reconstruction, if some postulates of the method were not consistent with modern ideas of the nature of the quasiplastic deformation process. On the basis of the above assertions, the next stage of investigations performed consisted in an analysis of the basic kinematic postulates for establishing their consistency with the developed stress–monitoring method, which already proved to be effective. This analysis demonstrated that in the developed algorithm of stress reconstruction no use was practically made of the postulate asserting the slip vector along the fault plane to coincide with the vector of tangent stresses. Essentially, in the case of graphical determination of the tensor of seismotectonic deformations, a new approach was used for its calculation together with the postulate of the similarity of the tensor of macrostresses to the tensor of macroplastic deformations, which corresponds to the assumption of the isotropy of the geomedium properties. Further analysis allowed to show the inequalities presented in [Rebetsky, 1996]

$$n_1^\alpha \mathbf{S}_1^\alpha > 0, \qquad n_3^\alpha \mathbf{S}_3^\alpha < 0 \tag{5}$$

which served as the basis for finding the space–time boundaries of the macrovolume, obtained in ref. [Sim, 1987; Angelier, 1984; Guschenko, 1982] as a consequence of the third postulate of the kinematic analysis, to actually be a consequence of the fundamental principles of plasticity theory generalized to the process of quasiplastic deformation of fractured media.

Indeed, we shall write the Drucker postulate [Drucker, 1994; Ivlev, Bykovtsev, 1971] asserting the work, done by an extra force during a complete charging and discharging cycle, not to be negative:

$$(\sigma_{ij} - \sigma_{ij}^0)^* \, d\varepsilon_{ij} + d\sigma_{ij} \, {}^* \, d\varepsilon_{ij} > 0 \tag{6}$$

Here, σ_{ij}^0 are the initial stresses determining the location of a point, plotted in the stress space, inside the charging surface [Klyushnikov, 1979]; σ_{ij} are the sought stresses and $d\sigma_{ij}$ and $d\varepsilon_{ij}$ are the increments of stresses and of the plastic part of deformations, respectively, obtained in the process of elastic–plastic deformation. One consequence of this postulate,

$$(\sigma_{ij} - \sigma_{ij}^0)^* \, d\varepsilon_{ij} > 0 \tag{7}$$

coincides with the known Mizes maximum principle [Mizes, 1928; Hill, 1956], defining the true stress state to be the stress, involving the maximum dissipation rate of mechanical work. Another consequence of the Drucker postulate is the inequality

$$d\sigma_{ij} \, {}^* \, d\varepsilon_{ij} > 0 \tag{8}$$

determining the stability of elastic–plastic deformation in small volumes and actually reflecting the presence of hardening in a material. Owing to the arbitrariness of σ_{ij}^0, from (7) positiveness follows of the expression

$$\sigma_{ij} \, {}^* \, d\varepsilon_{ij} > 0 \tag{9}$$

which means that to create a new irreversible deformation one should perform extra work. Expression (9) determines the dissipation rate of mechanical energy per unit volume. Note that the expression presented in ref. [Rebetsky, 1996] for "the homogeneity function" F_2

$$F_2 = \sum_{i=1}^{3}\sum_{j=1}^{3}(\sigma_{ij}\mathbf{S}_{ij}) \tag{10}$$

based on finding, for the investigated sample, the maximum projections of the vectors of shear stresses acting in the fault plane onto the direction of the displacement realised in this plane, is equivalent to (9). Therefore, F_2 can be considered the dissipative function characterizing elastic–plastic properties of the geomedium. Now we shall rewrite in the following form the component of "the homogeneity function" F_2 determining the contribution from the earthquake α, using the presentation of the tensor $\mathbf{S}$ in the principal axes of stresses:

$$F_2^\alpha = \sum_{i=1}^{3}\sigma_i n_i^\alpha s_i^\alpha \tag{11}$$

Since σ_i are the deviatory components of the tensor of the principal stresses, we rewrite (11), using expressions (4, 5) presented in ref. [Rebetsky, 1996], in the form

$$F_2^\alpha = [(1-\mu_\sigma)n_1^\alpha s_1^\alpha - (1+\mu_\sigma)n_3^\alpha s_3^\alpha] \tag{12}$$

We shall consider every slip along the shear fracture (the earthquake focus) as a result of a microact of plastic deformation $dF_2 = F_2^\alpha$, sxtending to it the requirement that the dissipation rate of mechanical energy be positive. Then, from inequalities (5) it follows that the direction of movement in a randomly oriented rupture plane with a normal n^α cannot be arbitrary. It is restricted by the requirement that the contribution to the tensor of seismotectonic deformations for each fault corresponds to a positive increment of the dissipation energy dF_2 on the tensor of true effective macrostresses. To fulfill the last condtion:

for $\mu_\sigma \Rightarrow 1$ it is necessary that $n_3^\alpha s_3^\alpha < 0$
when $-1/2 < n_1^\alpha s_1^\alpha < 1/2$ (13)
for $\mu_\sigma \Rightarrow -1$ it is necessary that $n_1^\alpha s_1^\alpha > 0$
when $-1/2 < n_3^\alpha s_3^\alpha < 1/2$

Thus, simultaneous fulfillment of conditions (5) provides for the requirement $dF_2 > 0$ being satisfied for any possible values of the coefficient of the kind of stress state. In other words, the cumulative AAS, the determination of which is the necessary condition for the creation of homogeneous samples, determines on a sphere of unit radius the areas of possible exit of axes of the principal tension and compression deviatory stresses, for which each movement along the shear fracture for the μ_σ unknown in advance yields a positive contribution to the dissipation function.

From (13) it also follows that there may always exist faults and versions of displacements along them, for which only one of the conditions (5) is fulfilled. However, the positive result of the stress–monitoring performed permits to claim that conditions (5) provide a good description of the interrelation between effective macrostresses and the character of microacts of quasiplastic deformation. This positive result of the reconstruction also permits giving the following interpretation of restrictions (5). In the process of quasiplastic deformation in the direction of maximum tension and compression of the stress tensor averaged over the macrovolume during the observation period, each act of shear displacement along the fault results in the appearance of only deformations of elongation and shortening, respectively.

Since function F_2 can be considered as the dissipative function, then, according to the Mizes maximum principle, F_2 achieves its maximum in the case of the true stress state. Note that the principle of determination of axes of the mean mechanism, realized in the algorithm of the stress–monitoring method, is identical with determining the maximum of the " homogeneity function" in the form of F_2. Therefore, fulfillment of the sufficient condition for the formation of a homogeneous sample is equivalent to determination of the exit points of axes of the principal stresses, for which the Mizes maximum principle is fulfilled, in the cumulative AAS.

In other words, in the stress–monitoring method, starting from the procedure for finding boundaries of the homogeneous macrovolume and up to the procedure for determining the stress tensor on the basis of the calculation of seismotectonic deformations in the form (1), no use is made of the third postulate of the kinematic analysis of shear fault. Restrictions (5) were actually applied, instead, having been demonstrated above to be a thermodynamic consequence of the quasiplastic deformation of fractured media.

All the above permits formulating the fundamental principles of quasiplastic deformation of fractured media:

1. The geomedium has a multitude of differing in their genesis defects in the form of surfaces of reduced strength oriented differently in space.

2. Every displacement along the shear slip plane results in variation of the tensor of effective stresses averaged over the space of the macrovolume containing a fault, and this tensor corresponds to the instantaneous structural–dynamic state of the geomedium in the time scale.

3. The direction of the average displacement along every shear slip plane coincides with the direction of the projection onto this plane of the vector of effective stresses for the tensor, averaged over the macrovolume space, which was in action at the moment of apperance of a fault.

4. Within the limits of each space–time scale level, determined by the sizes of fractures and by the time window used in averaging, the multitude of microacts of quasiplastic deformation in the form of displacements along faults and fractures causes formation of the tensor of macroplastic deformations, averaged over the space–time macrovolume, which is similar to the tensor of effective macrostresses and, generally speaking, differs from the tensor of effective stresses acting at every moment of time.

5. With respect to the stress tensor averaged within the space–time boundaries of the macrovolume, displacements over faults occur randomly, but so the elastic energy, dissipating during each microact of quasiplastic deformation, is positive (the stability of elastic–plastic deformation in small volumes), and in this case the maximum of the dissipation function of quasiplastic deformations for the SFD sample is achieved for the tensor of true stresses averaged within the limits of the space–time boundaries of the homogeneous sample (the Mizes maximum principle).

The five principles formulated for the process of quasiplastic deformation due to fault slip are fully consistent with the algorithm of the programming complex developed for stress–monitoring. These principles generalize many rules of quasiplastic deformation of mountain rock , which have been used earlier for reconstruction of the tensors of stresses and deformations [Rebetsky, 1996]. At the same time, they allow to explain a series of observed deformation peculiarities, such as the slip vector and the shear stress vector not coinciding on the breach plane, to understand the principles of division of the stress field into long–period and short–period components.

On the basis of the principles presented above, the following point of view can be expressed concerning the deformation process of the geomedium. When the intensity of the elastic–plastic deformation process is low, irreversible residual deformations are accumulated owing to displacements at the boundaries of grains and along the banks of microfractures, i.e. owing to defects at a low–scale level. The tensor of seismotectonic deformations of this scale is identical to the tensor of effective stresses within its long–period component determined by the character of boundary conditions and by the properties of a medium. When the intensity of deformation rises, the rate of energy dissipation increases, and, starting from a certain critical threshold, this increase cannot be provided for by defects of the scale level given. Defects of larger sizes become involved in the dissipation process of mechanical energy. Here, the first fractures are realized in accordance with the Mohr strength theory, and displacements correspond to the long–period stress tensor. Since, as a result of the shear displacement, the tensor of removable elastic deformations corresponds to the tensor of pure shear fault and may be similar to the long–period stress tensor only in special cases, then at the sites of shear faults the effective stress state deviates from the long–period component, and local in time and space variation of the stress field occurs, i.e. a ultra–short–period disturbance. As the density of the space distribution of fractures of this scale increases, the variations of the stress field can occupy more and more areas, comparable with the regional space scale, and act during relatively long periods of time, which represents the short–period component of the stress field. Note that the character of regional boundary conditions, which corresponds to the boundary conditions given in the deformation velocities in the earth's crust, apparently, remains unaltered during these relatively short periods of variation of the stress field (because of the greater extent of the strength sources acting at the regional level). Owing to the above, if the short–period variations – the deviations from the tensor of effective long–period stresses – become significant, then the fault formation that follows results in shear faults and slips along them originating, which reduces such deviations. It should also be mentioned that the parameters of the stress tensor determined at different points of space are related by a sole principle due to the stress field having to satisfy the law of momentum conservation or, in other words, to satisfy the equilibrium equations [Rebetsky, 1991]. In this sense, for the stress–strain state of the region under investigation as a whole fulfillment is required of the known extremum principle of minimum elastic deformation energy [Prager, 1958]. The latter suggests that, when regional boundary actions and properties of the medium remain unaltered during the time intervals investigated, short–period disturbances of the stress field cannot exist for a long time, and they should be considered as a local instability of irreversible character. So, ultimately, the tensor of seismotectonic deformations, forming due to defects of the consecutive scale level, tend to be similar to the tensor of effective stresses in its long–period component.

One consequence of these principles is the absence of the requirement of the maximum possible value of the normalized "homogeneity function", to be equal to unity, for the ideally collected SKDF sample [Rebetsky, 1996]. Moreover, considering the principles presented, the least values of the normalized "homogeneity function" should be observed for stress states with abosolute values of the Lode–Nadai coefficient differing significantly from the pure shear fault case (zero). In this respect, it is better to change the term "homogeneity function" to "stability function" of the process of quasiplastic deformation. Note, also, that the principles presented allow to proceed to develop methods for predicting the influence of every earthquake occurring on the type and character of successive earthquakes.

In conclusion, note that the regularities of the process of quasiplastic deformation described above are based on the five postulates, which owing to their experimental confirmation (reconstruction of the regional stress field confirming many known geological–geophysical data) are essentially principles. In this respect, the theory of quasiplastic deformation of fractured media, based on them, can be considered as a theory of principles.

5. Summary

1. Five principles are proposed of the quasiplastic deformation of fractured media.

2. A stress–monitoring program complex is developed on the basis of structural–kinematic data on the earthquake focal mechanisms.

3. The modern field of regional stresses is reconstructed for South–East Asia and the Oceania on the basis of the bank of focal mechanisms of crustal earthquakes and of the stress–monitoring complex.

4. It is demonstrated that the modern regional stress field is quite smooth within its long–period component, and that the regularity in its space variations is explained by subcrustal convective flows in oceanic zones of subduction and of continental collisions.

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