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MODELING STRESS-STRAIN STATE IN THE EPICENTRAL ZONE OF THE EARTHQUAKE 26.01.2001, M=6.9 (INDIA)

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Abstract. The genetic linkage of strong earthquakes with fault tectonics in continental regions gives grounds to assume that the high intensity gradient fields of tectonic stresses in local areas lead to tectonic ruptures (earthquakes) and following aftershock activity including co-seismic effects. We present the results of modeling of stress-strain state (SSS) in the epicentral zone before and after the strong tectonic earthquake 26.01.2001, M=6.9 in the north-western India. For this purpose, we used the author's software package of SSS calculation for heterogeneous blocks disturbed by a system of tectonic faults (elastic formulation of the problem). The calculations were based on the experimental geological, geophysical, and seismological data available for this region.

It is shown that areas of high stresses that were formed before the earthquake determine the epicenter position and location of strong aftershocks with $M \geq 5$, whereas the stress drop areas correspond to location of weaker aftershocks. The majority of aftershocks are concentrated in the region of static stress drops exceeding 5 MPa. Assuming the thickness of seismogenic layer equal to 25 km, the energy released is $\sim 2\cdot 20^{17}$ J, which exceeds the energy of seismic waves radiated in the rupture process of the 2001 earthquake by two orders.

The results of modeling indicate that the epicentral zone of the possible future strong earthquake corresponding to high stress area moves to the south. The results obtained can contribute to the possibility of forecasting the locations of strong earthquakes in seismically active regions based on SSS modeling of heterogeneous blocks disturbed by tectonic faults.

Keywords: modeling, stress-strain state, strong tectonic earthquakes, earthquake, aftershocks, forecast of earthquakes.

Introduction

Seismic activity of continental regions of the Earth is originally associated with fault tectonics of the crust and is determined by the level of its stress-strain state (SSS). In seismically active zones the external field of regional tectonic stresses creates local areas of stress concentration and thus causes the development of modern fault formation. Besides, active faults (the Cainozoic) are associated with epicenters of strong tectonic earthquakes [*Aktivnye* …, 2014; *Mian et al.,* 2007].

Local metastable areas are determined by the heterogeneity of the stress-strain state and strength of geological medium. Occurrence of such areas causes active development of seismicity including strong tectonic earthquakes [*Sobolev,* 2014]. Often the location of epicenters of main shocks is associated with zones of possible stress concentration in areas of fault end and crossing that occur due to the external field of tectonic stresses. Besides the aftershock activity of strong crustal earthquakes is in the depth range of 0-30 km, and length of newly formed rupture reaches tens of kilometers.

As a rule, the main shock of the crustal earthquakes is accompanied by one (Bath's law) or several strong aftershocks with $M \geq 5$ and hypocenters located at the depth of hypocenter of the main shock or closer to the surface. Besides it is assumed that the main part of the elastic energy of deformation is released in the form of seismic waves during the main shock, and the remaining part is implemented as aftershock process.

At the present time there is no single point of view on formation and development of the aftershock activity. The same situation is with the mechanism of occurrence of repeated strong earthquakes that can't be called aftershocks because their magnitude is comparable to the magnitude of the main shock [*Yanovskya and Servatovich,* 2011]. Due to this fact seismotectonic process should be studied in detail including the SSS analysis of epicentral zones. Heterogeneous block structure of the crust and interaction of tectonic faults create local areas of gradient stresses in the tectonic stress field that, ultimately, determine the characteristics of seismotectonic process in seismically active regions.

Mathematical modelling of SSS of heterogeneous block medium disturbed by a system of arbitrary oriented faults and located in the field of external tectonic stresses allows to distinguish areas of increased energy saturation of geological medium before and after strong crustal earthquakes (i.e. before and after the formation of extended rupture) and to consider them as areas of possible future strong seismic events.

The problem of appropriate representation of tectonic fault model (crack, seismodislocation, rupture, crack) that appears during modeling is well-known in continuum mechanics [*Osokina, Yakovlev, and Voytenko,* 2008]. There is also uncertainty in selection of the fault zone width and elastic parameters of dispersed material [*Kocharyan,* 2014]. However, the available geological data and modelling results of the fault zones allow accepting the fault width in the range from several hundred meters to 1.5-2 km [*Sherman S. I. et. al.,* 1992; *Shebalin,* 1992; *Rogozhin,* 2000].

The subject of the analysis presented in the paper is a result of SSS modelling of the region in the north-west of India where the earthquake occurred on 26.01.2001 with M=6.9 and hypocenter depth of 16 km. The choice of the region is determined by the high degree of knowledge of seismic process characteristics there and availability of results of *GPS*-observations, tomography of source zones and SSS modelling of epicentral zone of the studied earthquake. The SSS modelling was carried out for time periods before and after the mentioned strong event.

The modelling involves data on geological structure of the region, structural-tectonic scheme of fault tectonics, modern understanding of direction of dominating tectonic forces on the basis of earthquake focal mechanisms and *GPS*-observations, and also results of calculations of stress drop in aftershocks whose values reach 26.7 MPa.

The established connection between zones of tectonic stress concentration and localization of the main shock epicenter and areas of the following aftershocks can be considered as a possible methodological basis for the forecast of spatial tectonic process development in regions with seismicity associated with active crustal faults.

Method of SSS calculation for block heterogeneous massifs

Shikha, Gahalaut, and Vipul [2005] give the results of stress calculations in the region of seismodislocation simulating the rupture plane of the earthquake on 26.01.2001 in assumption that these stresses are a trigger mechanism of the aftershock process (trigger-effect). The estimated stresses are less than 0.2 MPa and are too small to cause spontaneous destruction of geological medium. In this regard, we can assume that stress concentration in the aftershock area at least is comparable with external field of tectonic stresses.

The software package for SSS calculation of heterogeneous block massifs disturbed by the system of tectonic faults in two-dimensional formulation was described earlier in several papers (see, for example, [*Morozov et al.,* 2008; *Kolesnikov, Morozov, and Tatarinov,* 2011; *Morozov, Kolesnikov, and Tatarinov,* 2011, 2012]). It is based on the idea of heterogeneous elastically isotropic block medium with lower moduli of elasticity compared to the blocks from external field of tectonic stresses.

In the present study a homogeneous elastically isotropic horizontal layer is modelled with the thickness significantly less than its linear dimensions. The layer is disturbed by a system of vertical faults. In calculations their length and width are regarded as independent values. In modelling, a fault (unlike seismodislocation) is an extended zone (of a partly dispersed material) coincidental with a system of echelon faults; the width of the zone is about 1 km and the modulus of elasticity there is significantly lower than the elasticity modulus of surrounding rocks.

The SSS calculation is performed by the method of finite elements in the form of displacements on the basis of tetragonal isoparametric elements. The method is chosen due to the conditions of minimization of total potential deformation energy for the entire massif as well as efficiency of its computer implementation.

Correlations between stresses and strains are taken averaged over the thickness of the layer according to the model of generalized plane stress state in the form of Hooke's law:

$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \end{Bmatrix} = \left[D(E^{(m)}, \nu^{(m)}) \right] \begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{xy} \end{Bmatrix}, \tag{1}$$

where σ_{xx}, σ_{yy}, and σ_{xy} are components of averaged integral stresses; ε_{xx}, ε_{yy}, and ε_{xy} are the corresponding components of the strain tensor; $E^{(m)}$ is the Young's modulus; and $\nu^{(m)}$ is Poisson's ratio of elasticity matrix of separate finite element used to introduce the material heterogeneity (fault) in elastic isotropic layer model in the form of

$$\left[D(E^{(m)}, \nu^{(m)}) \right] = E^{(m)} \left[1 - \left(\nu^{(m)} \right)^2 \right] \begin{bmatrix} 1 & \nu^{(m)} & 0 \\ \nu^{(m)} & 1 & 0 \\ 0 & 0 & \left(1 - \nu^{(m)} \right)^2 \end{bmatrix}. \tag{2}$$

When modelling SSS of geological massif, the external field of tectonic stresses is specified using the available geological-geophysical data in *yx* coordinate system (*y* is pointed to the north, *x* is pointed to the east). Distribution maps of components of averaged integral stresses σ_{xx}, σ_{yy}, σ_{xy} and stress intensity σ_i are analyzed:

$$\sigma_i = \left(\sigma_{xx}^2 + \sigma_{yy}^2 - \sigma_{xx}\sigma_{yy} + 3\sigma_{xy}^2 \right)^{1/2}. \tag{3}$$

Stress intensity is a measure of energy saturation of fragment of geological medium since the potential energy of changing the form is expressed as

$$U_{\text{ф}} = \frac{1+\bar{\nu}}{3\bar{E}} \sigma_i^2 \Delta V, \tag{4}$$

where $\bar{E}$ and $\bar{\nu}$ are the average elasticity moduli; ΔV is a volume.

In addition to seismic process, the fault formation is accompanied by an energy drop (in elastic formulation of the problem):

$$\Delta U = \frac{(1+\bar{\mu})\Delta h}{3\bar{E}} \left(\iint_{s_\sigma} \langle \sigma_i \rangle_{\text{I}}^2 \, dxdy - \iint_{s_\sigma} \langle \sigma_i \rangle_{\text{II}}^2 \, dxdy \right), \tag{5}$$

where $\langle \sigma_i \rangle_{\text{I}}$, $\langle \sigma_i \rangle_{\text{II}}$ are stress intensities (I) before and (II) after the fault formation; Δh is power of seismogenic layer; and s_σ is an area of the region of deformation energy released.

Values of released energy of static stresses were compared with the energy of elastic waves in tectonic fault formation.

Structural-tectonic scheme of the region of the earthquake studied and main results of seismological researches

Structural and tectonic SSS model of the earthquake region (Fig.1) is based on the scheme of fault tectonics given in [*Reddy and Sunil,* 2008]. The territory includes the region of Bhuj located in the north-west of India and is a region of high seismic activity. A number of strong tectonic earthquakes that occurred in the last two centuries are associated with fault tectonics of the region. Extended faults such as Nagar Parkar Fault (not marked in Fig.1) in the north of the region and Kutch Mainland Fault (KMF) in the south have sublatitudinal striking, as well as the less extended faults (North Wagad Fault (NWF), South Wagad Fault (SWF), etc.). According to geophysical studies, the crystalline basement lies at a depth of 2 to

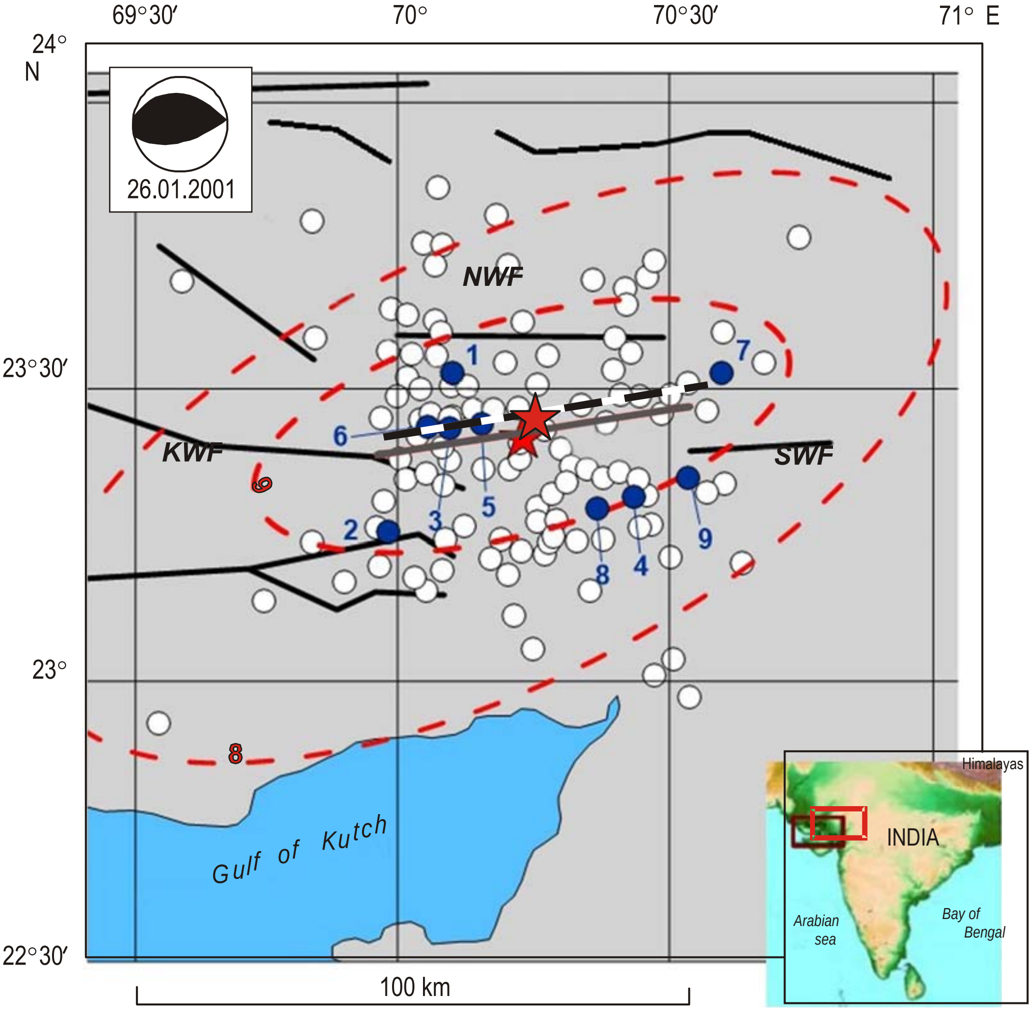

Fig. 1. Scheme of fault tectonics and seismicity of epicentral zone of the earthquake on 26.01.2001. Solid black lines are the main tectonic faults: KMF is the Kutch Mainland Fault, SWF is the South Wagad Fault, and NWF is the North Wagad Fault; dashed line is a supposed fault after the earthquake on 26.01.2001; circles are the aftershock epicenters (epicenters of aftershocks with M>5 are marked with filling; numbers near them correspond to the table below); dashed red lines are isoseismal lines with intensity. The insets show the location of the considered region on the map of India (*bottom*) and fault plane solution of the earthquake on 26.01.2001 (*top*)

5 km and the average depth of Moho boundary is ~35–43km [*Kayal and Mukhopadhyay,* 2006].

Results of GPS observations and analysis of focal mechanisms of strong earthquakes indicate that the dominating direction of axes of maximum compression stress is from north to south. The dominating source mechanisms correspond to reverse-strike-slip faulting with sharp dip of seismogenic ruptures [*Rapolu and Mandal,* 2014].

The isoseismal lines of the main shock of the earthquake of 26.01.2001 are given according to [*Sinvhal et al.,* 2003; *Narula and Chaubey,* 2004]. Aftershocks with M>2 (epicenters are shown in Fig.1) are recorded in the period from 26.01.2001 till 03.02.2001, in total 1428 events [*Reddy and Sunil,* 2008]. Aftershocks with M≥5 (filled circles in Fig.1) were recorded in the same period

The main parameters and depth of hypocenters of the main shock of 26.01.2001 and of the strongest aftershocks are given in the table (ISC data are used). Noteworthy is the fact that the first five strongest aftershocks with M≥5 were recorded within four hours after the main shock.

Focal parameters of the earthquake on 26.01.2001 and its aftershocks (*ISC*)

Event	Date	Time hh:mm:ss	Latitude φ °N	Longitude λ °E	Depth H, km	M
Main shock	26.01.2001	03:16:40.2	23.442	70.31	16	6.9
1	26.01.2001	03:33:31.8	23.522	70.076	24.9	5.3
2	26.01.2001	03:58:59.4	23.246	69.947	10	5.0
3	26.01.2001	04:23:42.3	23.421	70.119	10	5.1
4	26.01.2001	04:48:14.8	23.348	70.441	10	5.0
5	26.01.2001	06:04:51.5	23.431	70.216	10	5.0
6	26.01.2001	07:32:28.0	23.425	70.096	3.3	5.3
7	28.01.2001	01:02:10.7	23.532	70.598	10	5.9
8	03.02.2001	01:37:28.9	23.36	70.387	3.9	5.1
9	03.02.2001	03:04:32.7	23.66	70.52	10	5.3

Notes. In the first column, 1–9 are numbers of aftershocks.

More than 80 % of aftershocks that were recorded from 26.01.2001 till 03.02.2001 had sources at the depth of 5 to 28 km [*Kayal and Mukhopadhyay,* 2006]. The stress drop values in aftershocks reached 10-12 MPa at the maximum value of 26.7 MPa regardless of the depth of their hypocenters [*Rapolu and Mandal,* 2014].

Figure 2 shows the seismotectonic model of the source zone of the earthquake that was used in SSS modelling of the epicentral zone [*Kayal and Mukhopadhyay,* 2006].

Aftershock source mechanisms recorded to the east of the main shock correspond to the left lateral strike-slip, recorded to the west corresponds to the right lateral (see Fig.2). The main shock and all strong aftershocks, except for the first one, are recorded in the depth interval of 3 to 10 km (see Table).

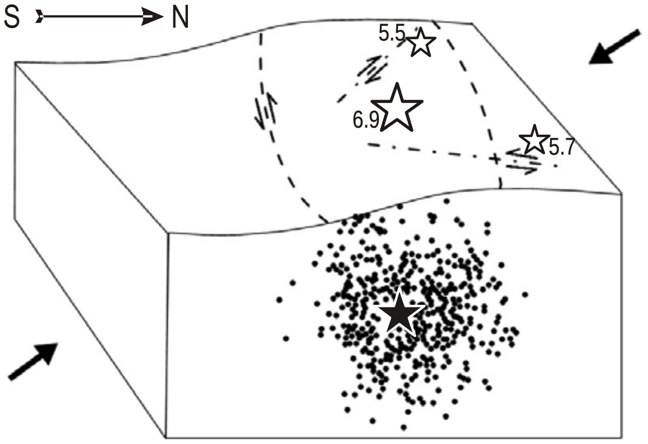

Fig. 2. Seismotectonic model of the earthquake on 26.01.2001 [*Kayal and Mukhopadhyay,* 2006]. Dashed lines are the main tectonic faults; dash-dotted lines are the axes of the supposed lineaments with directions of shears; big asterisk with filling is the earthquake hypocenter, without filling is its epicenter; small asterisks without filling are epicenters of strong aftershocks; circles are aftershock hypocenters. Numbers near stars are magnitudes of events.

SSS modeling of epicentral zone of the earthquake on 26.01.2001 before and after the event

The first stage included the SSS modelling of the fragment of geological medium with the area of ~150×150 km^2 (see Fig. 1). The fragment is represented as homogeneous elastic isotropic layer disturbed with the system of tectonic faults.

The dip of faults was considered to be vertical with the thickness of near fault zones of tectonic destruction amounting to 0.8 km. The layer was regarded as homogeneous and elastically isotropic with the elastic modulus $E=8\cdot10^3$ MPa and Poisson's ratio $\mu=0.25$. It is accepted that the elastic modulus of dispersed medium of tectonic faults in the model is lower by two orders. The calculation scheme can be amended in the presence of valid data.

Source mechanisms of strong earthquakes and maximum stress drop values of aftershocks of the earthquake on 26.01.2001 reaching 26.7 MPa [*Reddy and Sunil*, 2008] can govern the choice of stresses $\sigma_{yy}=-30$ MPa with the axis along the meridian. Acting stress σ_{xx} is accepted in the assumption of lateral resistance equal to $\frac{\mu}{1-\mu}\sigma_{33} = -10\ \text{МПа} = \sigma_{11}$, where $\mu=0.25$.

Figure 3 presents the maps characterizing the field of tectonic stresses of the considered region before the earthquake, i.e. before the formation of extended fault. Figure 3*a* is a map of stress intensity in the epicentral zone and Fig. 3*b* is a map of shear stresses.

On the general background of obtained values of σ_i lying in the range of 25-30 MPa the extended areas of high values of σ_i are seen at the ends of faults *KMF*, *NWF* and *SWF* (see Fig.3, *a*). In these zones, stress intensity reaches 65 MPa and above. It can be assumed that zones of high concentration of σ_i are zones of new fault initiation, not excluding the possibility of a new rupture in the area of maximum gradient of stress intensity [*Morozov et al.,* 2008; *Morozov, Kolesnikov, and Tatarinov,* 2011].

In Fig. 3 *b* in the epicentral zone of the earthquake, there are two zones of high shear stresses reaching ~20 MPa of the opposite signs in the west and east relative to the epicenter

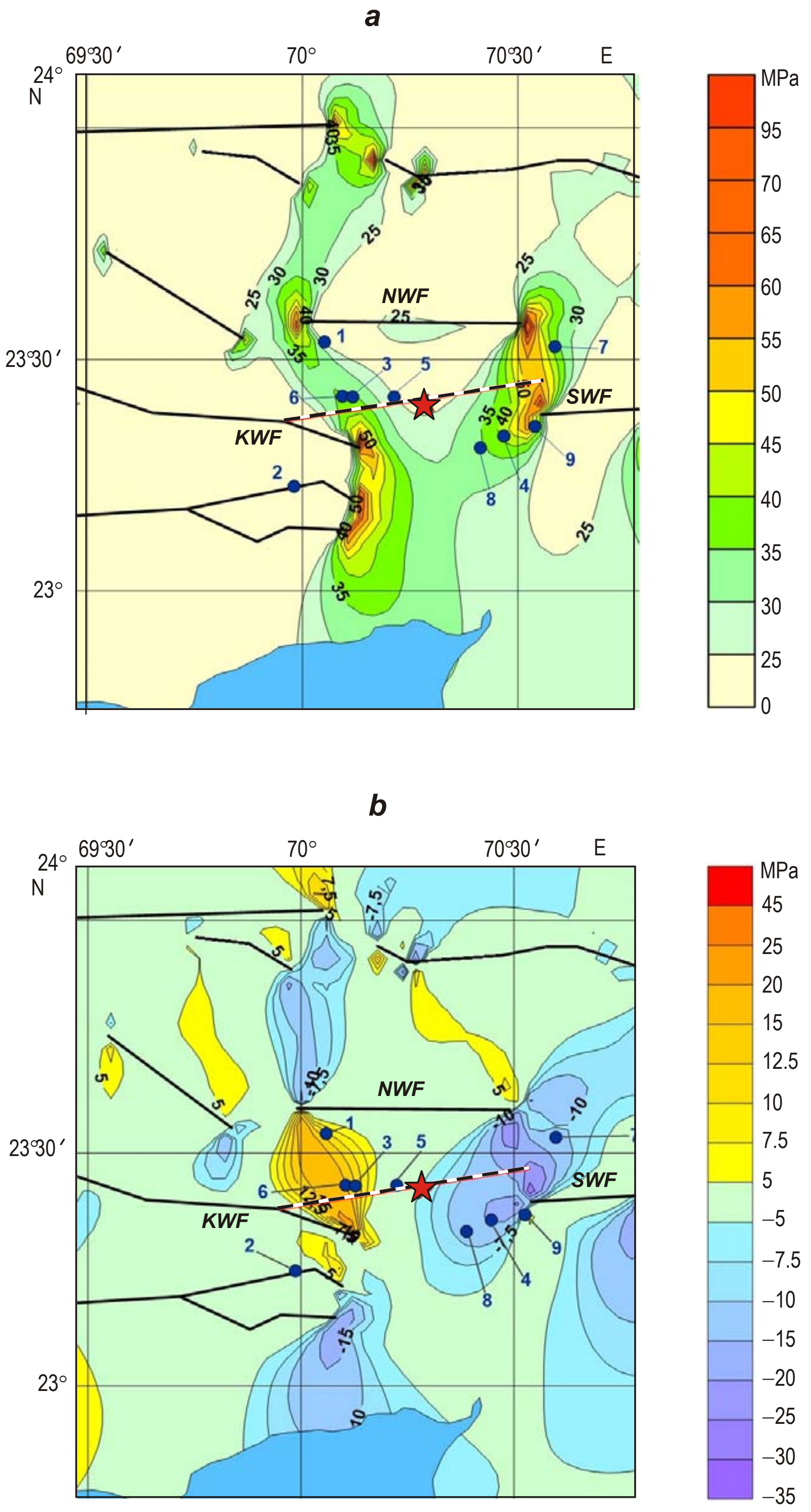

Fig. 3. Maps of (*a*) stress intensity in the epicentral zone and (*b*) shear stresses before the formation of the main fault (blue circles are aftershocks with $M \geq 5$, see the table)

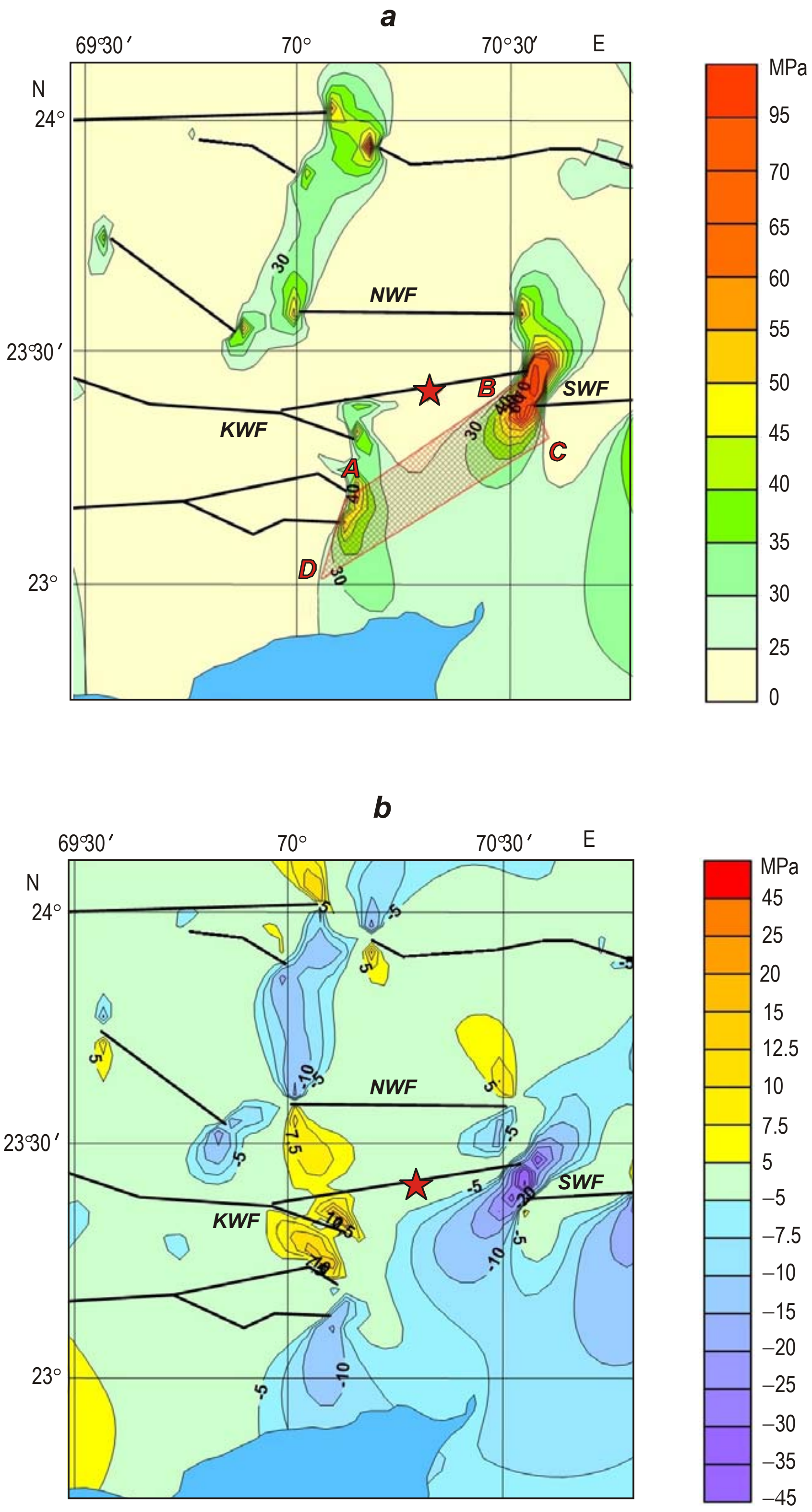

Fig. 4. Maps of (a) stress intensity σ_i and (b) shear stresses τ_{xy} after the fault formation. *ABCD* in *a* is a border of a possible new strong earthquake.

of the earthquake of 26.01.2001. In the epicenter of the future earthquake, $\sigma_{yy} \approx -32$ MPa and $\sigma_{xx} \approx -15$ MPa.

In the next stage SSS in the epicentral zone was calculated taking into account the fault caused by the earthquake (Fig.1). Position and length of seismogenic fault were determined according to the method by N.V.Shebalin [1997]: the length of the fault is ~60 km (isoseismal line with intensity 9 was used) and striking is 85°. The dip of fault is accepted as vertical. Practically the seismotectonic model of focal area given in [*Reddy and Sunil,* 2008] and presented in Fig. 2 is used. Figure 4 gives the maps of σ_i (Fig. 4*a*) and shear stresses τ_{xy} (Fig. 4*b*) after the fault formation.

The SSS of the epicentral zone significantly changed after the fault formation. Figure 5 shows a map of stress differences $\Delta\sigma_i$ calculated according to the formula (5). Maximum stress drop values σ_i reach 20 MPa. Two areas of aftershock localization recorded to the west and east of the earthquake epicenter during the first week after the main shock (1428 aftershocks) are located in zones of maximum stress drops in the range from 10 to 20 MPa.

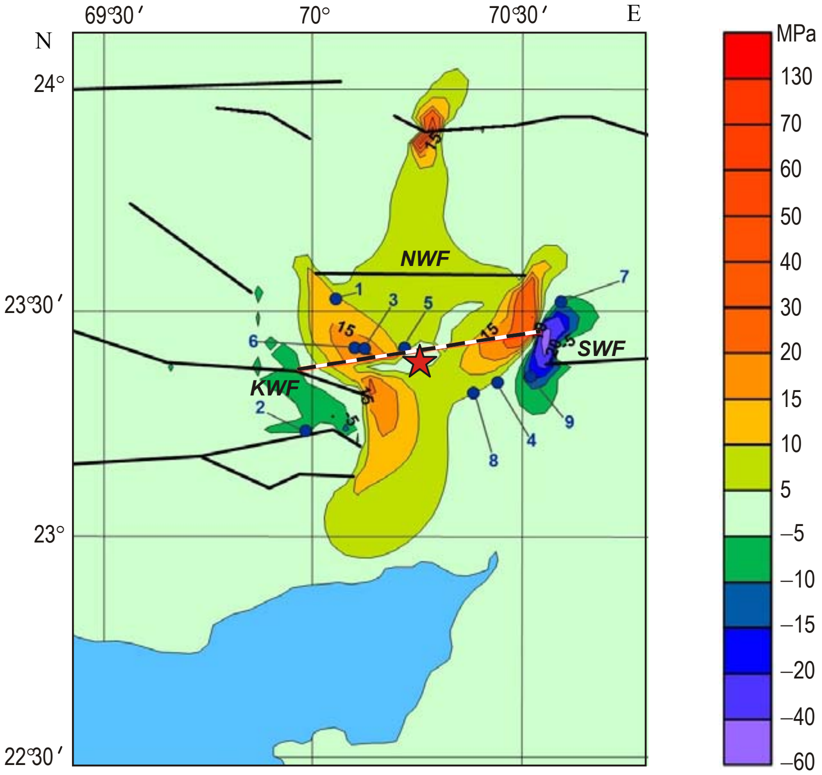

Fig. 5. Stress difference before and after the fault formation. The scale of absolute values of differences, MPa, is given to the right; other notations see in Fig.1

The range of stress drop values of 0-5 MPa covers a significantly larger area. At the same time the area of stress growth is seen to the west and east of the epicenter (Fig. 5).

If the volume of seismogenic layer is $\Delta V = S_0 \Delta h \approx 6 \cdot 10^4$ km^3, where S_0 is an area of stress intensity released and Δh is a power of seismogenic layer equal to 25 km, then the amount of static stress drop ΔU is ~$2 \cdot 10^{17}$ J with the accepted average value $\langle \bar{\sigma}_i \rangle$=10 MPa. This value is significantly above the energy of seismic waves defined by the formula

$M = \frac{2}{3}\left[\lg E_s - 4.8\right]$, where M is an earthquake magnitude; E_s is a released seismic energy. Taking for this earthquake M=6.9 we will obtain $E_s = 10^{15}$ J.

The static stress drop is defined as

$$\Delta U = E_c + E_d + E_a, \tag{6}$$

where E_c is a released energy of seismic waves; E_d is an energy expended on formation of the fault surface and dispergation of geomaterial within the fault zone including the heat loss; and E_a is a residual energy realized in the aftershock process. It should be emphasized that E_c includes the released potential energy of elastic deformations in the volume (at least) of aftershock process during the earthquake, i.e. during the formation of extended fault. Taking into consideration the actual nonlinearity of elastic properties of geological medium, it should be assumed that aftershock activity in the epicentral zone is associated with relaxation of stresses formed before the main shock and with the following formation of a new field of tectonic stresses after it, as well as with contribution of environment dispergation during the aftershock activity.

It can be assumed that stress drop in the earthquake epicentrral zone leads to changes in hydrogeological regime of groundwater. The flow of groundwater to the area of partially released stresses leads to activation of the aftershock process that attenuates as the stress accumulated before the main shock releases.

Maximum stresses released after the formation of the main rupture are

$$\left\langle \Delta\sigma_{yy} \right\rangle_{\max} = 30MPa,$$
$$\left\langle \Delta\sigma_{xx} \right\rangle_{\max} = 16MPa,$$
$$\left\langle \Delta\tau_{xy} \right\rangle_{\max} = 12MPa.$$

The result obtained is comparable with calculations of stress drops in aftershock sources using spectral characteristics of seismic waves. The maximum stress drops reach 27.5 MPa [*Kayal and Mukhopadhyay,* 2006].

In local zones, stresses after the main shock increase: $\Delta\sigma_{yy}$=10 MPa, $\Delta\sigma_{xx}$=20 MPa, $\Delta\tau_{xy}$=12–14 MPa.

The redistribution of stresses after the rupture formation is not instantaneous. Its active stage corresponds to the time of aftershock activation and continues, at least, in the process of aftershock activity. Actual nonlinearity of elastic properties of block medium allows for the possibility of creep [*Benioff,* 1961], and consequently the extended in time compensation SSS process in the epicentral zone. It is important to emphasize that instantaneous stress release during the formation of extended rupture contributes to destruction development of preliminary stressed zones where the level of stress concentration is close to critical.

Strong events with M≥5 recorded within first four hours after the main shock (see table) are associated with areas of released stress intensity and maximum shear stresses calculated in the SSS model of epicentral zone before the earthquake (Fig. 3). It can be assumed that the released stresses of spherical tensor contribute to realization of accumulated stresses before the main shock.

Aftershock activity of epicentral zone recorded within a week after the main shock (Fig. 1) corresponds with areas of released stress intensity and maximum shear stress zones to the east and west of the earthquake epicenter.

Aftershock mechanisms registered to the east of the epicenter corresponds to the right-lateral and to the west, to the left-lateral strike-slip [*Reddy and Sunil*, 2008]. The obtained calculated values of shear stresses in these zones correspond to experimental data (Figs.2 and 3, *b*).

The limit energy capacity of volume element of geological medium at background stress intensity ~25 MPa amounts to ~$3.2 \cdot 10^4$ erg. Therefore, the development of destruction of geological medium and, consequently SSS changes in the area studied should be expected for the values exceeding this value.

Conclusions

We admit that the term “SSS modelling of the earthquake epicentral zone” is not fully correct due to a number of assumptions and suppositions (from the accepted structural-tectonic scheme of the region of “rupture plane” orientation to the restrictions of the method used for SSS modeling of block heterogeneous massif). However, it is supposed that the set of the results obtained gives hope for some physical and mechanical adequacy of SSS model of epicentral zone state of the earthquake, 26.01.2001, in the north-west of India (M=6.9) before and after the main shock.

In this regard it is obvious that the resulting tectonic fault significantly changes the SSS of modelling area. Analysis of the changed SSS gives the possibility to determine locations of possible new strong tectonic earthquakes, at least, in the framework of formulation of geophysical research in forecast purposes.

The obtained results give some basis to assume that new SSS of epicentral zone of the earthquake on 26.01.2001 with M=6.9 (after the formation of the extended tectonic fault) includes dangerous zones that are formed during the process of long energy upload by regional field of tectonic stresses. It is logical to assume that the zone of future tectonic event is shifted to the south (Fig.4, *ABCD* area), i.e. stresses released due to the fault formation of 26.01.2001 must be compensated by external field of tectonic stresses up to a certain ultimate critical level.

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