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Satellite Monitoring of Seismic Hazard Area Geodynamics Using The Method of Lineament Analysis

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Abstract - Results from monitoring of seismically endangered regions using the method of automated lineament analysis of satellite imagery are presented. The possibility of applying this method is based on the assumption that the lineament systems in space imagery are tightly correlated with seismogenic dislocations and react to modifications in the strain pattern caused by changes in the field of Earth crust stresses.

A sliding window method was applied for more precise identification of the site of the forthcoming seismic event. This enabled us to carry out detailed lineament analysis of space imagery fragments covering the region of the possible earthquake. Results are also presented from detection of the epicentral zone for the Parkfield earthquake (September 28, 2004), implemented through operative monitoring of the geodynamic situation in central and southern California using images taken by TERRA and AQUA satellites.

Keywords: space monitoring, lineament analysis, earthquake precursors, seismically hazardous regions

1. INTRODUCTION

Despite a high level of research aimed at developing methods for earthquake forecasting, and considerable sums invested in the solution of this problem, the reliability of such forecasting remains rather low (Sobolev, Ponomarev, 2003; Bondur, Zverev, 2005a). That is why it is necessary to look for new types of earthquake precursors and to further develop the theory of earthquake forecasting. Reaching this aim requires development of efficient methods for the monitoring of earthquake precursors.

At present, along with conventional methods of seismological monitoring, new methods, including those that use satellite imagery, have also been introduced. Application of space methods and their combination with in situ methods allows us to significantly increase the reliability of forecasting major seismic events. One of the most promising methods of space monitoring is the method of operative geodynamics analysis for seismically hazardous territories (Bondur, Zverev, 2005 a,b,c). This method is based on the detection of lineament systems variation in satellite images.

As a rule, lineaments form a well-expressed network with several dominating directions well corresponding to planetary fissuring. By their spread length, lineaments are classified into transcontinental, trans-regional, regional and local ones. Lineaments are expressed in satellite imagery in different ways. They can form either narrow sharp lines, linear zones having an inner pattern, or wide (up to hundreds of kilometers) belts composed of extended lineament zones. Therefore, the level of imagery generalization is of great importance when analyzing lineaments of different ranks and depth of location (Bondur, Zverev, 2005 b).

It has been determined that deeper structures are better seen in satellite images of low spatial resolution having a higher level of generalization. Therefore, for the monitoring of processes preceding an earthquake, it is expedient to use images with a spatial resolution of about several hundreds meters (Bondur, Zverev, 2005 a,b). Thanks to such generalization, it becomes possible to track the dynamics of wide lineament zones corresponding to entire systems of faults.

This work will discuss results from practical application of the proposed method for forecasting earthquakes. This method uses dynamics of lineament systems detected in space imagery as a precursor of these seismic events.

2. ORGANIZATION OF SPACE MONITORING AND DATA PROCESSING

From July - October 2004, operative monitoring of geodynamic earthquakes precursors was carried out for the southern and central parts of California. For this purpose we conducted operative systematization and processing of space images taken by the TERRA and AQUA satellites (MODIS sensor, spectral range 620 - 670 nm, resolution 250 m). Only cloud-free images, fragments of which covered the area studied, were used for the analysis.

Automated lineament analysis of satellite images was performed using the modified version of the special computer program LESSA (Zlatopolsky, 1997). Because the spatial orientation of lineament zones is much better presented by their rose diagrams of lineament directions, new software modules were added that enabled us to build these diagrams at any threshold level of lineament manifestation and with high angular discretization (Bondur, Zverev, 2005 a,b,c).

After analyzing the current seismic situation in the studied seismically hazardous region using large fragments of satellite images, for further study these fragments were scanned using windows of size 400x400 pixels (100x100 km^2) and 800x800 pixels (200x200 km^2). All these windows were then subjected to automated lineament analysis.

As was determined in (Bondur, Zverev, 2005 a, b, c), during earthquake preparation there is an increase in the number of cross-cutting and transverse lineaments and this number decreases after the earthquake. This is a geodynamic precursor of earthquake. After detection of such precursors in the large window, windows were reduced to above mentioned size. This enabled us to study local areas in details. This technique allowed us to detect the precursors of major earthquakes that occurred in central California in 2004: September 18 (M=5.5 and M=5.4) and September 28 (M=6.0, Parkfield). It also allowed us to determine their epicenter zones. Here we shall consider an example of results from monitoring of the Parkfield earthquake that took place on September 28, 2004 (M=6.0).

3. RESULTS OF MONITORING AND THEIR ANALYSIS

Fig. 1a presents six examples of space images taken by the TERRA satellite on September 21, 24, 26, 28, as well as October 1 and 4, that were used to study the seismically hazardous region (Bondur, Zverev, 2005 a,b). Fig. 1 also displays the following:

- Density of lineaments in each large fragment (400x400 km^2) of the satellite images (Fig. 1b);
- Rose diagrams of lineament orientation that were built by processing these fragments (Fig. 1c).

Analysis of rose diagrams enabled us to determine that the prevailing direction of lineaments is from the northwest to the southeast in all the images processed. This corresponds to the general spread of the large San Andreas tectonic fault in California (Bondur, Zverev, 2005a,b,c). This fault about 960 kilometers long is not a single rupture, but a zone of tectonic dislocations with multiple branches. It also represents the convergence frontier between the Pacific and North American lithosphere plates which is the reason of heightened regional seismicity. The second and third directions of lineaments are, respectively, oblique and transverse in relation to the first one (passing through the San Andreas zone almost at the right angle to the fault). As the pattern of lineaments and their rose diagrams show, the number and size of oblique and transverse lineaments increased before the earthquake and decreased after it (Bondur, Zverev, 2005 a, b, c).

Oblique lineaments are well expressed on all the diagrams and rose diagrams shown in Fig. 1, except for September 21 and October 4, 2004. They are especially well seen in the satellite image taken on September 26, 2004, i.e. 2 days before the main shock (M=6.0) happened on September 28, 2004.

For more detailed study of the geodynamic precursors of earthquakes near the epicentral zone, processing of fragments of smaller size was carried out using the sliding window method. Each source space image was scanned using windows of size 800x800 pixels (200x200 km^2 and 400x400 pixels (100x100 km^2). The fragments obtained in this way cover almost all the studied area. Processing of fragments having such dimensions allowed us to study local geodynamic structures situated in the epicentral zone and its vicinity, and to establish how the lineament systems change with distance from the epicenter of seismic events.

Let us consider the results of lineament analysis for 200x200 km^2 fragments of images taken on September 28, 21, 26 and October 1, 2004 (see Fig. 1). Fig. 2 displays the tectonic map of California showing footprints of space image fragments taken on different days, and lineament rose diagrams. In these Figures, solid lines are used to show the boundaries of fragments A, B, C, D, E and F. Fragment B1 and fragments of larger - 400x400 km^2 size that were analyzed during the preprocessing are shown by dashed lines (Fig. 1). The epicenter of the Parkfield earthquake (September 28, 2004) is situated at the center of fragment B.

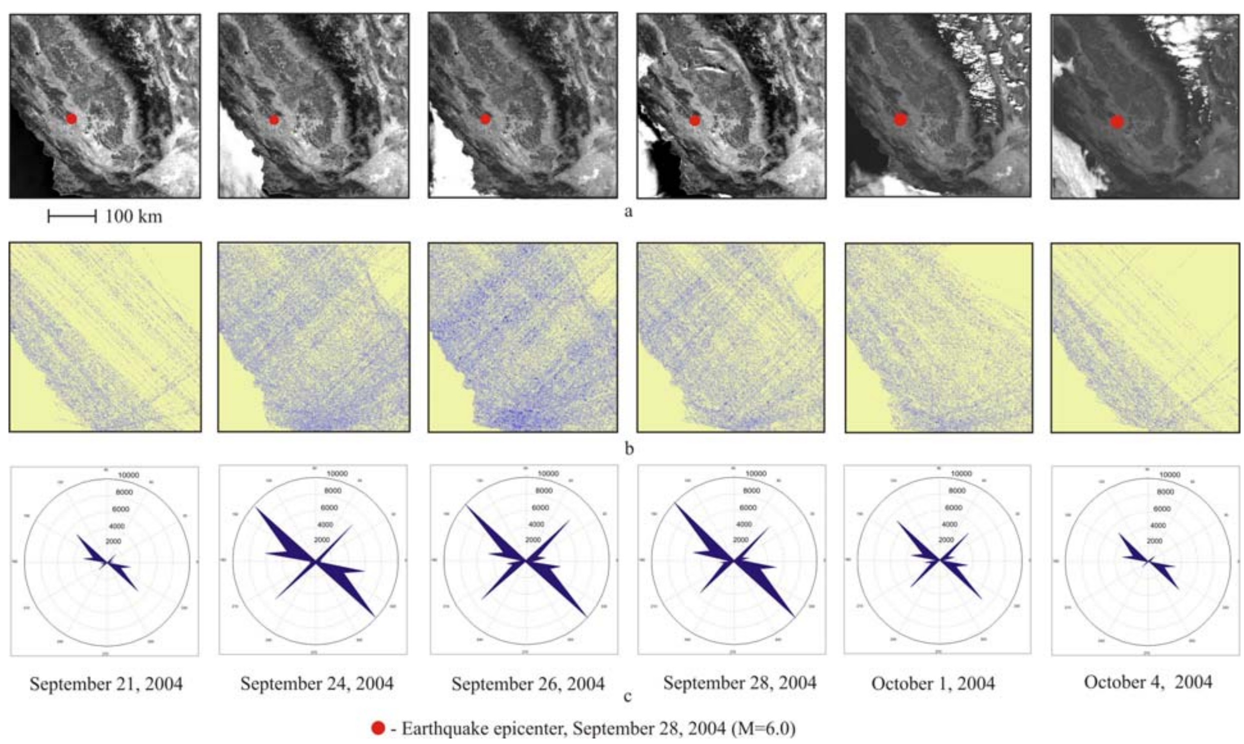

Figure 1. Dynamics of lineament systems for the earthquake of September 28, 2004 (M = 6.0)
a) processed image fragments; b) lineament densities; c) rose diagrams of lineament directions

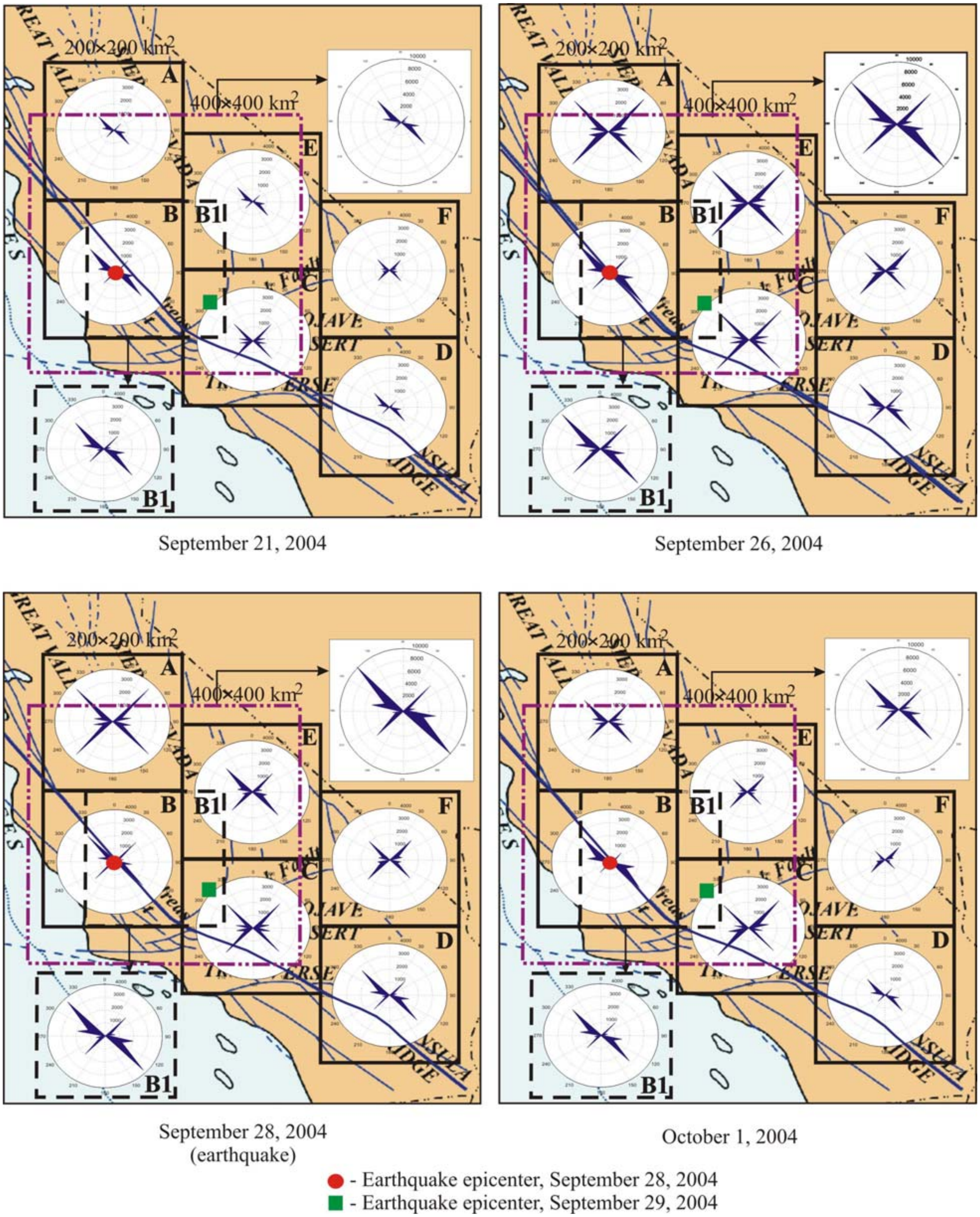

Figure 2. Detailed lineament analysis of satellite image fragments for the earthquakes of September 28 (M=6.0) and September 29 (M=5.0), 2004

The rose diagrams built using detailed processing, as in the previous case, show two prevailing directions of lineaments. The first of them coincides with NW-SE extension of the San Andreas fault, the second one is almost perpendicular to the direction of this fault. For all the four scenes analyzed above the greatest number of longitudinal lineaments is detected in fragment B. This is quite natural, since the San Andreas fault completely intersects this part of the region studied. For the scene taken on September 21, 2004 (one week before the earthquake), the least number of longitudinal and transversal lineaments is detected in all the fragments.

Two days before the Parkfield earthquake (September 26, 2004) and three days before another earthquake (M=5.0) occurred on September 29, 2004, 180 km to the southeast of the studied region (see fragments B1 and C in Fig. 2), all analyzed fragments show growth in the total number of lineaments, and fragments A, C, E and F show that the number of transverse lineaments is greater than the number of longitudinal ones. Fragments A, B1, C, D, E and F of the image taken on September 28, 2004 (Fig. 2c), about 5 hours before the Parkfield earthquake, show a similar pattern, but the greatest number of transverse lineaments is seen in fragment C (epicenter of the quake).

The fragments (except C) extracted from the image taken on October 1, 2004 (Fig. 2d) show a decrease in the number of longitudinal and transverse lineaments. The number of transverse lineaments in the fragment C was more than the number of longitudinal ones because the epicenter of the earthquake (September 29, 2004, M=5.0) located in this fragment. The maximum number of transverse lineaments was seen in the fragments B and C (close to the epicenter). Similar results were obtained for the fragments of smaller size: 400x400 pixels (100x100 km^2).

The sliding window method for lineament analysis of satellite imagery allows us to better detect the location of the epicentral zone of the forthcoming seismic event.

Scientifically and methodologically, this method is confirmed by the regularities in the development of seismogenic faults detected by geological and geophysical observations, as well as by the avalanche-unstable fracturing model (Sobolev, Ponomarev, 2003). The kinetic concept of strength stipulates that long-term stresses in any solid material, including rocks, result in gradual formation of fractures. When the distribution of these fractures in the geologic environment is statistically uniform, and their number and size depending on slowly increasing loads grows gradually, some favorably located fractures will merge and create fractures of larger size. When a critical density of such fractures is attained, an avalanche-like process of their merging will start as a result of interaction between the stress fields of closely located fissures. During this process, a relatively small number of extended faults are gradually formed. Their merging into a narrow zone lead to the macro-dislocation of rocks (i.e. an earthquake). The process of fissure formation consists of three stages (Sobolev, Ponomarev, 2003). During the first and longest stage a gradual accumulation of fractures caused by slowly increasing tectonic stresses takes place in the rocks. At this stage shift fractures are mainly developed, though torn-off fracture may also appear. When the critical density of fractures is attained, the environment passes into the second stage of fracture interaction. Fracturing starts to sharply increase due to the destruction of inter-fracture bridges and their merging into larger fractures. The speed of general deformation in rocks is increased by movements taking place along the fracture edges. At this stage avalanche interaction and fissure merging are taking place. At the third stage an instable deformation localized in a narrow zone of future macro-rupture develops. Inside this zone an accelerated formation of fractures continues. In the adjacent rocks the fractures stop their development because of the partial removal of strain. They become inactive and their presence has no significant effect on physical features of rocks.

So, during the preparatory phase of strong earthquakes an increase in the number of fractures and their contraction to the plane of newly-formed fault takes place. This is manifested as the growth of number of lineaments observed in the satellite images. These lineaments are oriented along the extension of the major fault, transverse and oblique lineaments appearing as well.

On the whole, our study shows that the lineaments detected in space imagery can serve as medium-term and short-term precursors of earthquakes. On the basis of the proposed method it is possible to organize space monitoring of seismically hazardous territories.

4. CONCLUSION

Our study shows that automated lineament analysis of space images is highly reliable, responsive and efficient for geodynamic monitoring of seismically hazardous regions. Seismic monitoring based on this analysis could allow us to forecast not only the time, but also the location of earthquakes. For this, it is necessary to study all seismically endangered zones using the sliding window method, i.e. to interpret overlapping areas (fragments of satellite imagery) along the whole length of seismogenic faults (such as the San Andreas).

Thus, the proposed method for analysis of lineament system dynamics using satellite images, in combination with other methods, can be used for operative monitoring of seismically hazardous regions with the purpose of studying and forecasting major seismic events.

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