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GEOLOGY

Structural–Dynamic Relationships between the East Sikhote Alin Volcano-Plutonic Belt and Its Folded Basement

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The East Sikhote Alin volcanoplutonic belt (ESAVB) extending along the coasts of the Sea of Japan and Tatar Strait is over 1000 km long and 35–40 km wide on average. Similar to other elements of the East Asian volcanic belt, the latter represents a structure with the continuous development mode being superimposed or crossing protostructures of the eastern margin of the Asian continent regardless of their types and ages. The study of structural–dynamic relationships between the basement that existed during synchronous dislocations and superimposed volcanic complexes reveals the geodynamic formation conditions of volcanic belts.

The East Sikhote Alin volcano-plutonic belt was formed in the Late Cretaceous–Paleogene. It is composed of sedimentary–volcanogenic and volcano-plutonic rocks resting unconformably upon the folded basement represented largely by Lower Cretaceous terrigenous strata deformed into a system of open and isoclinal folds with a dominant northeastern strike (azimuth 40°–60°) and complicated by imbricate updip–thrusts. In contrast to the basement, no dominant regional folded and dislocated systems were defined in volcanics during mapping. They demonstrate only fragments of folded–bedded structures with variable strikes and dip angles as well as numerous fractures also oriented differently (largely, normal faults), the formation of which is thought to be related to local stresses during volcanoplutonic magmatism. Most researchers share the opinion that volcanics represents a superposed complex with its own dislocation type independent from tectonics of the Early Cretaceous folded basement. The discovery of a system of NNE-trending sinistral strike-slip faults with displacements amplitudes in the Late Cretaceous amounting to a few tens of kilometers made it possible to infer that the East Sikhote Alin volcano-plutonic belt was formed in response to Late Cretaceous activation of strike-slip faults [2–4]. Such geodynamic conditions should result in the formation of ensembles of regularly oriented both folded structures and fractures characteristic of rocks overlying active strike-slip faults. This makes it crucial to study structures that developed in Late Cretaceous volcanics presumably in response to displacements along strike-slip faults.

The problem of relationships between dislocations in the East Sikhote Alin volcanoplutonic belt and its folded basement was considered in earlier works [1, 3, 4]. This paper presents the results of the statistical analysis of all the available data on orientation of elements measured for folded structures and dislocations during long-term mapping and research works. The genesis of statistically defined regularities in spatial relationships between fractures and folds was interpreted using the structural–paragenetic method. For the correct solution of the assigned task (in order to exclude the influence of local factors), the study was conducted in two large segments of the East Sikhote Alin volcano-plutonic belt located hundreds of kilometers away from each other: the northeastern flank of the belt (Samarga ore district) and its central part (Kavalerovo–Dal'negorsk ore district).

The statistical analysis of structural elements measured in the basement of the volcanic belt yielded the following results. The maximums of measurements for dip elements in Lower Cretaceous sedimentary complexes (Figs. 1D, 2C) point to the dominant role of folds largely with steep (60°–85°) limbs and NE strikes (azimuth 40°–50°) conformable with the prevalent orientation of the Sikhote Alin fold system. The maximums of measurements obtained for fractures with signs of displacement (Fig. 1E) indicate development of dominant steep (dip angle 60°–90°) planes with prevalent northeastern strikes parallel to the general orientation of strike-slip faults in the Sikhote Alin belt, the Central Sikhote Alin strike-slip fault (its main fracture) included. In the last diagram and others, the latter is used as a reference structure for the analysis of statisti-

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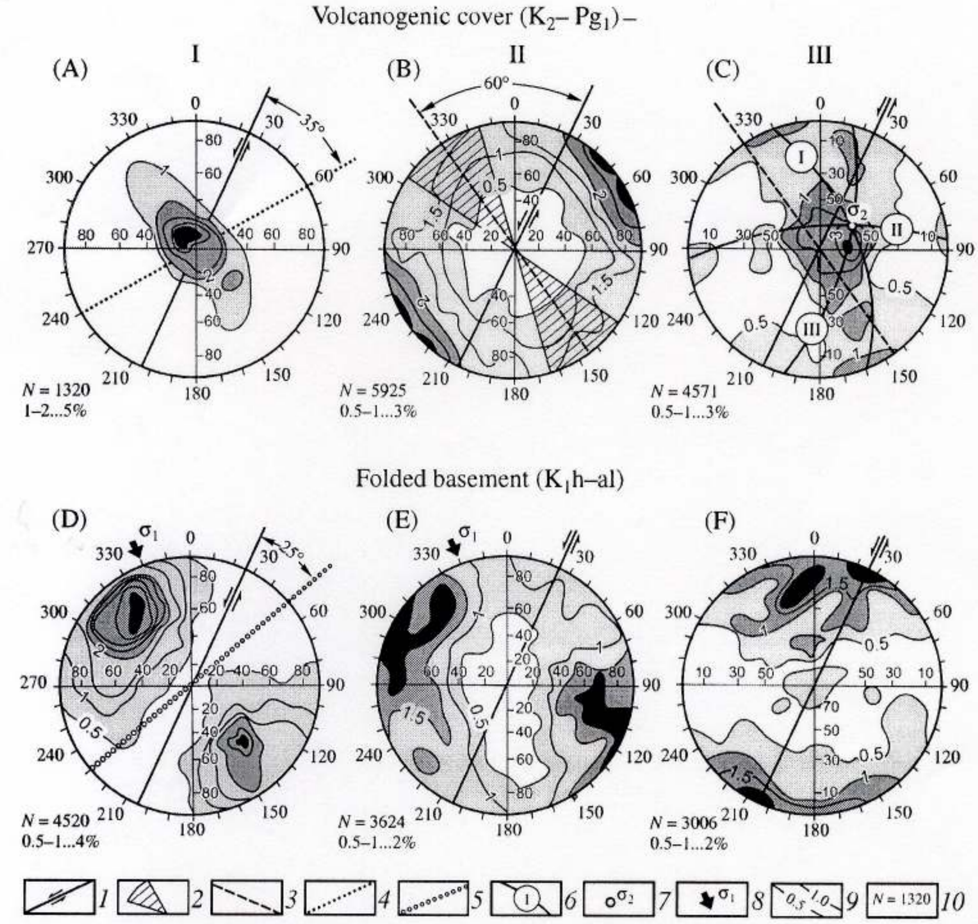

Fig. 1. Relationships between folds and fractures in the volcanogenic cover and folded basement based on statistical analysis (northeastern flank of the East Sikhote Alin volcano-plutonic belt). (I–III) (vertical rows) Diagrams (Wolfe grids, upper hemispheres) of orientations yielded by mass measurements of bedding elements (I), fractures with displacement signs (II), and tectonic striation (III). (*1*) strike of the Central Sikhote Alin sinistral strike-slip fault; (*2*) sector of dominant steep fractures in volcanics; (*3*) averaged strike of dominant fractures in volcanics; (*4, 5*) strike of folds in volcanics (*4*) and underlying basement (*5*); (*6*) localization zones of tectonic striations with different dip angles; (*7*) projection of the average compression strain axis at the sphere surface; (*8*) main compression strain oriented at approximately 45° with the Sikhote Alin system of sinsitral strike-slip faults; (*9*) density isolines of bedding poles (A, D), fractures (B, E), and sliding striae dips (C, F); (*10*) number of measurements of bedding elements (I), fractures with displacement signs (II), and tectonic striae (III).

cal data on dominant trends in fractures and folds. The maximums of measurements for tectonic striation (Figs. 1F, 2D) reflect largely its gentle dip angles (0°–30°) and strike parallel or near-parallel to steep NNE-dipping planes (Fig. 1E) confirming the kinematics of regional strike-slip faults established in the Sikhote Alin belt. The dominant directions of fold and fracture systems defined by the statistical method as well as their cinematic characteristics appeared to be identical to strikes and kinematics of the mapped regional structures in the basement of the volcanic belt. In fact, statistical analysis was tested as a method for defining dominant fold–fracture systems and was then used for the reliable assessment of dislocation characteristics in the volcanogenic cover.

Unlike the folded basement, the volcanogenic cover is characterized by gently inclined homoclines deformed into dominant brachyform folds with low-angle limbs. At the same time, folding demonstrates a distinct tendency for development of linear NE-trending folds (Figs. 1A, 2A) generally identical to that of the fold system in the basement (Figs. 1E, 2C). Detailed analysis reveals some discordance in the position of folds with different dip angles of limbs (Fig. 2A). The system of folds with relatively gentle limbs (dip angles up to 50°) is oriented largely in the northeastern direction (azimuth 60°) and at an angle of approximately 35° relative to the strike of the Central Sikhote Alin strike-slip fault, while folds with steeper (up to 85°) limbs are oriented on average at 40° NE similar to the strike of compressed folds in the basement (Fig. 2C). Two main inferences are derivable from the analysis of the volcanogenic cover folding. First, contrary to previous views, the Late Cretaceous volcanogenic cover is characterized by the relatively distinct tendency for development of the regional NE-directed fold system, which is oriented at an acute angle relative to sinistral NE-trending strike-slip faults, which implies its formation in response to the activity of strike-slip faults in the basement. Second, during their compression, primary folds with gentle limbs rotated counterclockwise in accord with rotation in zones of sinistral strike-slip faults.

The fractures with displacement signs defined in Late Cretaceous volcanics are largely steep to vertical (Fig. 1B). They are variably oriented, although characterized by a distinct dominant vector indicating that most fractures were formed in the northwestern sector (305°–345°) at an average angle of 60° relative to sinistral NE-trending strike-slip faults in the basement of the belt. According to field observations, many NW-oriented fractures are characterized by dextral displacements, in addition to normal faults. The displacement along these fractures is confirmed by near-horizontal tectonic striation of the northwestern strike (Figs. 1C, 2B). Dissimilar to dominant strike-slip faults in the basement (Figs. 1F, 2D), Late Cretaceous volcanics demonstrate prevalent normal faults largely with steep to vertical tectonic striation (Figs. 1C, 2B). In general, tectonic striation is localized in three zones, the intersection of which marks the surface projection of the middle compression stress axis dipping southwestward at an angle of 60° (Fig. 1C). The steep position of the middle compression axis combined with the near-horizontal main compression (NW 40°) point to the prevalent displacement component.

The measurements of steep (70°–90°) fault planes with gentle (0°–30°) tectonic striation were selected for estimating the orientation of strike-slip faults in volcanics relative to their counterparts in the basement (Fig. 3A). The rose diagram compiled for strikes of strike-slip faults in the basement is characterized by two main maximums: I (25°) and II (355°). In volcanics, they are reflected in two maximums of strikes: I' (335°) and II' (305°). The angles between maximums I–I' and II–II' are 50°. This gives birth to the assumption that the maximums of dextral strike-slip faults in volcanics are related to activation of the corresponding maximums of sinsitral strike-slip faults in the basement. This assumption is consistent with the results of the well-known experiment in [5] (Fig. 3B). It may be considered that the northwestern system of dextral strike-slip faults represent Riedel's shears that formed in response to Late Cretaceous activation of NE-trending sinistral strike-slip faults in the basement. The prolonged activity of NE-trending sinistral strike-slip faults in the basement during the Late Cretaceous was likely responsible for transformation of Riedel's shears into extension structures, which resulted in wide development of normal faults in volcanics and their control over dike magmatism and ore bodies, as is established by the corresponding studies.

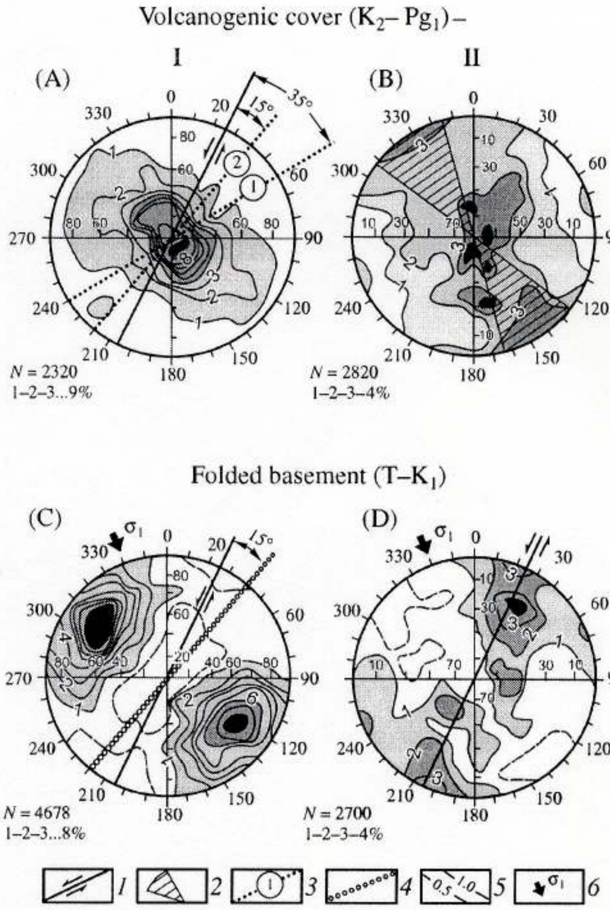

Fig. 2. Relationships between folded structures and tectonic striation in the volcanogenic cover and folded basement (central part of the East Sikhote Alin volcanic belt). (I, II) (vertical rows) diagrams (Wolfe grids, upper hemispheres) of orientations yielded by mass measurements of bedding elements (I) and tectonic striation (II). (*1*) Strike of the Central Sikhote Alin sinistral strike-slip fault; (*2*) sector of dominant steep fractures in volcanics; (*3*) strike of folds in volcanics at their early (1) and subsequent (2) development stages; (*4*) strike of folds in the basement; (*5*) density isolines of bedding poles (A, D) and tectonic striation (B, C); (*6*) main compression oriented at an angle of approximately 45° relative to the Sikhote Alin system of sinistral strike-slip faults.

The presented data allow the following main inferences.

(1) The statistical analysis of bedding elements in sedimentary rocks reveals the well-developed dominant NE-trending fold system in the Early Cretaceous basement underlying volcanics. It also confirms development of the dominant system of steep (up to vertical) fractures with low-angle tectonic striation, the NE orientation of which is identical to the strike of sinsitral strike-slip faults in the Sikhote Alin belt. Relative to the system of strike-slip faults, the system of folds is ori-

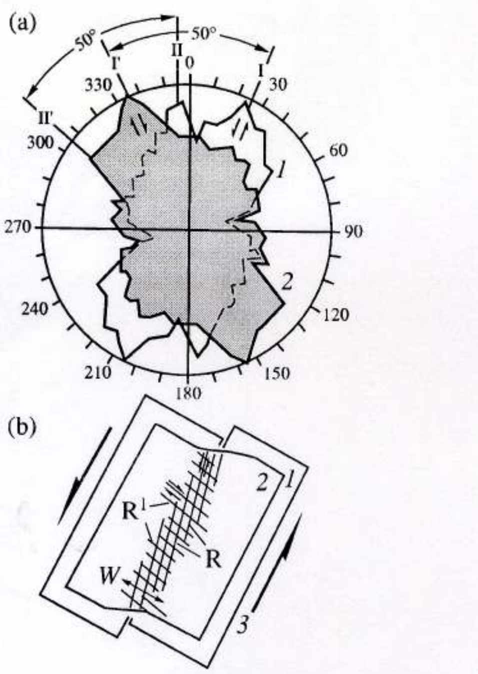

Fig. 3. Dominant orientation of strike-slip faults in the volcanogenic cover and basement (a) and their correlation with the results obtained by Riedel's experiment (b). (a) Rose-diagrams compiled for directions of strike-slip faults in the basement (*1*) and volcanogenic cover (*2*) based on 1336 and 1520 measurements, respectively. (I–II) measurement maximums obtained for directions of sinsitral strike-slip faults in the basement, activation of which was likely responsible for the formation of the corresponding (I', II') maximums of dextral strike-slip faults in the volcanogenic cover. (b) Model of Riedel's experiment [5]. (*1*) rigid plates; (*2*) plastic material (clay); (*3*) direction of plate displacement (sinsistral strike-slip faults); (R) Riedel's shears (synthetic strike-slip faults); (R_1) conjugate Riedel's shears (antithetic strike-slip faults); (*W*) width of the displacement zone.

ented at an acute angle, which is consistent with the position of folded parageneses related to sinistral strike-slip faults. Consequently, the basement structures of the volcanic belt were formed in the Early Cretaceous in response to displacements along these fractures due to near-meridional regional compression.

(2) In addition to local dislocations likely related to volcano-plutonic processes, the Late Cretaceous volcanics host a system of dominant brachyform folds, although with a distinct tendency for development of linear elements of the northeastern strike. The oblique orientation of folds in volcanics relative to strike-slip faults in the basement points to the formation of folds in volcanics under continuing active movements along a system of NE-trending sinistral strike-slip faults in the basement during the Late Cretaceous.

(3) Despite variable orientation of different dislocations in Late Cretaceous volcanics (largely normal faults), they are dominated by fractures that were formed in the NW sector (305°–345°). In addition to normal faults, this system of fractures includes dextral strike-slip faults. It is oriented at an angle of approximately 60° relative to the system of NE-trending sinistral strike-slip faults developed in the basement, which is consistent with the Riedel's shears developed, according to some studies, in rocks overlying active strike-slip faults. Consequently, dominant fractures in volcanics were formed in response to activation of sinistral NE-trending strike-slip faults in the basement.

(4) The entire system of dominant folds and fractures in the Late Cretaceous volcanogenic cover was formed under the influence of the activated system of sinistral NE-oriented strike-slip faults in the belt basement. This inference conflicts with traditional views, according to which movements along strike-slip faults in the eastern margin of Asia were replaced in the Late Cretaceous by subduction settings. Development of Late Cretaceous volcanic belts in response to movements along strike-slip faults is confirmed also by their morphogenetic characteristics. The linear morphology of continental-margin volcanic belts is explained by their relation to concealed strike-slip faults. The latter determine both tremendous lengths of belts and accompanying magmatic processes since activation of these fractures results in the formation of extension structures in the continental crust and development of stress fields favorable for migration of magma from different levels [2–4].

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