Tectonic Structures of the Mangazeya Ore Cluster (Verkhoyansk Range, NE Asia)

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Abstract. The Mangazeya ore cluster is located in the central part of the West Verkhoyansk sector of the Verkhoyansk fold-and-thrust belt, in the zone of junction of the Kuranakh anticlinorium and the Sartang synclinorium. High-tonnage Ag deposits and occurrences are concentrated here, which are thought to be associated with the zones of longitudinal strike-slip faults and bedding-plane thrusts. Structural studies were conducted in the dome and the eastern limb of the Endybal anticline, in the areas of the Nizhne-Endybalskoe, Verkhne-Endybalskoe, Bezymyannoe, Vertikalnoe, Sterzhnevoe, and Semenovskoe ore deposits. The Endybal asymmetric anticline 10-15 km wide and 60 km long, with a wide gentle dome is the major tectonic structure of the territory. The conducted structural and statistical analyses of tectonic structures in the study area allowed better understanding of their specific features and trends in development. Morphology of the fold structures indicates manifestation of concentric-type folding produced by bending of strata as a result of bedding-plane slipping. The same NS orientation of the cleavage and folds gives unanimous evidence for their genetic relationship and formation in the conditions of EW horizontal compression. It is established that the structural paragenesis represented by fractures, normal faults, and extension structures in the hinge zone of the concentric Endybal anticline, which determines the general tectonic pattern of the Mangazeya ore cluster and controls localization of ore bodies, was formed at the first deformation stage or in course of bedding-plane faulting and fold-and-thrust deformations rather than as a result of strike-slip motions. It is shown that strike-slip motions of the second deformation stage not only produced new structures but also inherited disturbances of the previous stage. It is found that normal faults in the study area formed synchronously with the fold-and-thrust structures. A similar orientation of the major faults and the strike-slip faults suggests that the regional faults have strike-slip kinematics. The occurrence of different types of tectonic deformation is controlled by rock lithology.

1. Introduction
The Mangazeya ore cluster is located in the central part of the West Verkhoyansk sector of the Verkhoyansk fold-and-thrust belt, in the zone of junction of the Kuranakh anticlinorium and the Sartang synclinorium [1] (figure 1). High-tonnage Ag deposits and occurrences are concentrated here, which are thought to be associated with the zones of longitudinal strike-slip faults and bedding-plane thrusts [2, 3]. The structural studies were conducted in the dome and the eastern limb of the Endybal anticline, in the areas of the Nizhne-Endybalskoe, Verkhne-Endybalskoe, Bezymyannoe, Vertikalnoe, Sterzhnevoe, and Semenovskoe ore deposits (figure 2, A).
2. Tectonic structures

The Endybal asymmetric anticline 10-15 km wide and 60 km long, with a wide gentle dome is the major tectonic structure of the territory (figure 3). Dipping of the rocks in its eastern limb is very steep, up to overturned, while the western limb is gentle (few degrees). The core of the anticline is composed of the Upper Carboniferous-Lower Permian strata of the Kygyltas Fm., with its limbs made of the Lower Permian deposits of the Khorokyt and Echiy Fms. of the Verkhoyansk clastic complex. The anticline was presumably formed, like other fold structures of the region, above a blind thrust duplex built of Middle to Upper Paleozoic carbonate and clastic-carbonate rocks with evaporates, and a detachment thrust is traced at the base of the Middle Carboniferous unit [1] (figures 2, B, 3). The rock masses are cut by Cretaceous granodiorite porphyry dikes and a subvolcanic body (Endybal stock) of plagiogranodiorite-porphyry composition [2]. In constructing the balanced cross-section (figure 3) we followed the technique described in [4]. According to our estimate, the minimal shortening of the deformed rocks in the folding process ranges up to 20%.

A cylindrical geometry of the Endybal anticline and other folds of smaller size is well seen on the diagram of measurements of orientation elements with the poles of bedding distributed in the arcs of great circles (figure 4, A). The fold structures have a NS strike. Studies of their morphology showed virtually the same thickness of beds both in the crests and limbs. This is indicative of the concentric-type folding produced by bending of strata as a result of the bedding-plane slip. Such folds and ruptures of various kinematics are established in sedimentary rocks represented by sandstones interbedded with siltstones and mudstones. The clayey deposits are affected by cleavage deformation. This indicates that various types of tectonic deformation are controlled by rock lithology. An example is an exposure on the left bank of the Endybal R., 4.5 km upstream from the mouth. Here, in the eastern limb of the Endybal anticline there is an outcropped horizon of sedimentary rocks with a total thickness of about 15 km. It is composed of two thick (5 m) sandstone beds which are faulted by a system of longitudinal and transverse tectonic fractures and separated by a sequence of cleaved siltstones. The sandstones are draped into large asymmetric concentric-type folds, while the over- and underlying siltstones are pierced by a throughgoing cleavage.
Figure 2. Geologic sketch map of the Mangazeya ore cluster (A), modified from [2] and schematic stratigraphic column of the Upper Paleozoic and Triassic strata (B):

rocks: 1– Quaternary; 2– Early Triassic; Upper Permian: 3 – Dulgalakh, 4 – Delenzha, 5 – Tumara Fms.; Lower Permian: 6 – Khabakh, 7 – Echiy, 8 – Khorokyt Fms.; 9 – upper member of the Kygyltas Fm.; Carboniferous-Lower Permian: 10 – lower member of the Kygyltas Fm.; 11 – igneous rocks of Cretaceous age: a – plagiogranodiorite porphyry, b – granodiorite-porphyry dikes, c – dolerite dikes; 12 – deposits; 13 – faults (N – Nyuktama fault zone); 14 – cross-section line; 16 – sandstones, 17 – siltstones, 18 – mudstones, 19 – limestones, 20 – dolomites.
Widespread is an intense non-penetrative cleavage of the clay beds, cutting 15-30 cm thick sandstone interlayers contained in them. The cleavage is linear in form (figure 5, A) and sometimes bends around the scattered round and oval-shaped sandstone concretions up to 1 m in diameter. The thickness of the microlithons varies from 1 to 10 (rarely more) mm. The cleavage surfaces have a persistent NS orientation over the entire study area, with dip azimuths from 65-75° to 244-255° and dip angles of 70-90° (figure 4, B). The lower (up to 30°) dip angles are characteristic of the bedding-plane cleavage observed in clay layers in sandstones. The same NS strike of the cleavage and folds (figure 4, A, B) strongly suggests their close genetic relationship and formation under conditions of EW horizontal compression.

It is only in one segment of the eastern limb of the Endybal anticline that a cleavage with a different orientation from the regional NS strike is observed. On the left bank of the Endybal R., 0.7 km downstream from Selten creek, there are found two aleuroargillite blocks separated by a bedding fault expressed as a 0.5 m thick crush zone. In the lower block, the cleavage is directed NE (figure 4, B), while the upper block retains the N-NW orientation of the regional cleavage. The dip azimuths and dip angles of the sedimentary rocks in both blocks are virtually the same as well as the extent and form of the cleavage. One may assume that deviation from the regional cleavage strike observed in this particular segment is caused by the rotation of the lower block along the planes of the bounding bedding-plane faults.

Figure 3. Balanced cross-section through the Endybal anticline and the Ergennake syncline:

rocks: 1 – Lower Triassic; Upper Permian: 2 – Dulgalakh; 3 – Delenzha, 4 – Tumara Fms.; Lower Permian: 5 – Khabakh, 7 – Khorokyt Fms., 8 – upper member of the Kyglyta Fm.; Carboniferous-Lower Permian: 9 – lower member of the Kyglyta Fm.; 10 – Middle-Carboniferous; 11 – Middle-Upper Paleozoic, undifferentiated; 12 – plagiogranodiorite porphyry; 13 – thrust; 14 – strike-slip fault; 15 – stratigraphic boundaries; 15 – cross-section line A–B shown in figure 1.
Figure 4. Diagrams: poles to bedding (A), cleavage (B), fractures (C), slickensides of strike-slip faults (D), normal faults (E), extension fractures (F) and major faults (G) of the Endybal anticline: equal-area projection, lower hemisphere; n – number of measurements

The bedding-plane thrusts are localized in a 20 m thick horizon of the Kygyltas Fm. composed of interbedded sandstones and siltstones. The most common type of deformation in this horizon is boudinage of the sandstone beds. The clayey deposits, often schistose parallel to the bedding plane, take an active part in dividing the sandstones into lenses and boudins of various shapes (figure 5, B). They intrude into the sandstones from below along vertical or inclined small-scale thrusts, occupying the interboudin spaces and destructing the sandstone beds either partly or completely.

The NS-trending thrusts intersect the sandstone strata in a step-like manner (figure 6, A) at angles of 15-30°. They are sometimes expressed as zones of en-echelon extension fractures filled with vein material (figure 6, B). Deformations of this type occur rarely in the study area and thus they were not involved into statistical analysis and no diagram was constructed for them. However, they may be interpreted as thrust structures resulted from the bedding-plane faulting. Asymmetrical folds of sandstones and cleavage of siltstones on the left bank of the Endybal R. also may be due to the bedding-plane faulting that occurred at early stages of the fold and thrust deformation when the sedimentary rocks had a subhorizontal bedding. At the late stage of deformation, these structures proved to be within the eastern limb of the Endybal anticline.
The bedding schistosity of clay layers intercalated with sandstones is not necessarily associated with the bedding-plane faulting. It may also be due to crushing of the clays as a result of sliding of the sandstone beds along one another during the formation of the concentric Endybal anticline.

The rock strata are deformed by tectonic fractures and ruptures of various types. The steeply dipping fractures form two orthogonal systems of NS and EW orientation (see figure 4, C and figure 5, C). With respect to the structure of the Endybal anticline, the NS- and EW-oriented fractures are longitudinal and transverse, respectively. The fractures’ planes may be very large in size, sometimes forming the walls of the exposures (figure 5, D). On the planes of the longitudinal fractures there are observed slickensides formed as a result of later strike-slip motions (Bezymyanno deposit). On the whole, our observations led further support to the existence in the study area of the earlier established [3] orthogonal system of NS and WE tectonic fractures which are referred to the Late Mesozoic tectonic structures.

The strike-slip faults in this territory received more attention from researchers than other deformations since they are believed to be the major structures defining the tectonic pattern of the region and controlling localization of mineralization [3]. One such structure of regional scale is the Nyuktama strike-slip fault which is traced along the whole length of the eastern limb of the Endybal anticline. All the rest minor strike slips and other faults confined to its zone are interpreted as feathering and accompanying structures. According to orientation of striae on slickensides, the
direction of planes of the dextral and sinistral strike-slip faults is virtually the same. As seen from the diagram (figure 4, D), the strike-slip faults have three main trends – EW, NS, and NW-SE. The first two directions correspond to the orientation of tectonic fractures, and the latter one forms an independent system. Note that the strike-slip faults often inherit the cleavage planes as evidenced by the slickensides with subhorizontal striation observed on the cleavage surfaces.

Figure 6. Structure and morphology of thrusts (A, B) and normal faults (C, D) in the dome of the Endybal anticline

A – Porfirovy creek; B, C, D – left bank of Sirelendya creek; d – felsic dike.

The normal faults in the study area are as widespread as the strike slips. In terms of orientation they are grouped into NS and EW systems (figure 4, E), and with respect to the structure of the Endybalskoe anticline they are longitudinal and transverse, respectively. The normal faults are steeply dipping ruptures, with well-defined kinematics and the amplitude of displacement from 5-30 cm to a few meters (figure 6, C). Along their planes there extend quartz veins, and in the Verkhne-Endybalskoe deposit area the normal faults associate with felsic dikes (figure 6, D).

We carried out structural analysis of the veins oriented at an angle to bedding. Measurements of their planar elements showed that they also may be grouped into two systems with NS and EW directions (figure 4, F), which practically do not differ from the above-described systems of tectonic fractures and normal faults (figure 4, C, E). This is well seen at the Bezemyannoe deposit where vein material fills in the NS and EW-trending fractures. Other forms of extension fractures include enechelon veins in sandstone beds, e.g., NS- and NW-trending veins observed on the left banks of
Sirelendya and Fedor-Yuryage creeks, respectively. In the latter creek, the en-echelon veins are truncated and displaced as a result of the small-scale bedding-plane faulting.

**Figure 7.** Sequence in the formation of fractures and normal faults resulted from extension of the upper part of the concentric-type anticline with a wide dome, modified from [6]:

A – cross-section of anticline, B – top view of anticline. 1 – direction of compressive stresses; 2 – direction of bedding-plane slipping; 3 – direction of tensile stresses: a – in figure A, b – in figure B; 4 – tentative boundaries of beds; 5 – extension fractures; BP – bedding-plane fractures; I, II, III – formation stages of anticline and extension fractures.

Structural analysis of major faults, which are expressed in the exposures as the crushed zones of sedimentary rocks, among them mineralized, having a thickness of 0.5 – 2.5 m and bounded by the planes of rupture disturbances, revealed several groups of these structures with different orientation. In the area of the Vertikalnoye deposit, the faults are directed NW, while those on the left banks of Sirelendya creek and the Endybal R. have NS and, to some extent, EW and NE orientation (figure 4, G). It is established that the major faults show trends corresponding to those determined for the strike-slip faults (figure 4, D), which suggests their strike-slip kinematics.

As seen from the diagrams (figure 4, C–G), all of the major faults, fractures, and veins have similar orientation, and were, likely, formed, at one time. Thus, we identified an early structural paragenesis including various types of disturbances and later deformations that were superposed on the previous structures and inherited their directions.

The early stage of the Late Mesozoic tectonic deformation is marked by folding and thrusting throughout the Verkhoyansk fold-and-thrust belt. It was the time of formation of practically all tectonic disturbances known in the region: concentric-type folds, including the Endybal anticline,
overthrusts, bedding-plane thrusts, boudins, cleavage, tectonic fractures (shear and extension) as well as strike-slip and normal faults.

The thrusting process is nearly always accompanied by the formation of strike-slip faults, though on smaller scale, normally in the form of lateral ramps sometimes bounding the flanks of the thrusts. In the outer (convex) part of concentric anticlines, transverse and longitudinal tensile stresses develop [5], which produce longitudinal and transverse tectonic fractures (shear and extension) and normal faults (figure 7, A, B). The transverse normal faults also form when the anticline bends along its long axis and undulates. The origin of the longitudinal shear and extension fractures and normal faults is related to extension processes in the dome of the anticline, which lead, in some cases, to the formation of grabens (figure 7, A). Along with the longitudinal and transverse cross-cutting fractures, extensional structures are formed in the hinge zones of concentric-type anticlines (figure 7, A, II and III).

The above discussed specifics of the mechanism for the formation of concentric folds explains rather well the origination in the Late Mesozoic of tectonic shear and extension fractures and normal faults of similar orientation synchronously with the formation of folds and thrusts in the outer part the Endybal anticline. The dense network of conjugate cross-cutting longitudinal and transverse extension fractures with numerous cavities of extension is located in the hinge zone of the Endybal anticline or at the transition site from the gentle dome to the steeply dipping eastern limb, where it controls the localization of ore bodies and felsic dikes. This highly deformed, mineralized area in the hinge zone of the Endybal anticline, extending from the left bank of the Endybal R. in the south to the right bank of Mangazeika creek in the north, was earlier considered as the Nyuktama strike-slip fault zone [3].

This zone seems to have formed during the second deformation stage as evidenced by the same trend of extension fractures and strike-slip faults, as well as by subhorizontal orientation of striae on slickensides of longitudinal fractures (figure 4, C). This suggests that faults penetrating deep into the basement of the Verkhoyansk rock complex in the given region, such as the Nyuktama fault, could have formed even in the first deformation stage. Subsequently, at the second deformation stage, these faults that originated in the intensely disrupted hinge zone of the Endybal anticline were renewed as strike slips. However, along with the reactivation of the early faults, new strike-slip faults of NW orientation were developed in the study area.

3. Conclusions
The conducted structural and statistical analyses of tectonic structures in the study area allowed better understanding of their specific features and trends in development.

1) Morphology of the fold structures indicates manifestation of a concentric-type folding produced by bending of strata as a result of bedding-plane slipping.

2) The same NS orientation of the cleavage and folds gives unanimous evidence for their genetic relationship and formation in the conditions of EW horizontal compression.

3) It is established that the structural paragenesis represented by fractures, normal faults, and extension structures in the hinge zone of the concentric Endybal anticline, which determines the general tectonic pattern of the Mangazeya ore cluster and controls localization of ore bodies, was formed at the first deformation stage or in course of bedding-plane faulting and fold-and-thrust deformations rather than as a result of strike-slip motions.

4) It is shown that strike-slip motions of the second deformation stage not only produced new structures but also inherited disturbances of the previous stage.
5) It is found that normal faults in the study area formed synchronously with the fold-and-thrust structures.

6) A similar orientation of the major faults and the strike-slip faults suggests that the regional faults have strike-slip kinematics.

7) The occurrence of different types of tectonic deformation is controlled by rock lithology.

The presented results of structural studies may be useful in solving the questions of tectonic pattern, morphology, control, and trends in localization of ore bodies in other areas of the Verkhoyansk fold-and-thrust belt.

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