Tectonic Conditions for the Formation of Structures of the Sakandzha Ore District (Selennyakh Ridge, NE Asia)

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Abstract. The Sakandzha gold-ore district occurs in the north-western margin of the Selennyakh allochthonous block of the Omulevka terrane forming part of the Kolyma-Omolon microcontinent (Verkhoyansk-Chersky orogenic belt, NE Asia). Tectonic structures of the Sakandzha ore district were formed in two stages of the Late Mesozoic deformation: thrust and strike-slip fault ones. Formation of the fold-and-thrust structures of the early Late Mesozoic deformation stage within the Selennyakh block and its thrusting, in the form of a thrust sheet, over the fold structures of the Tuostakh-Polousnyi zone in Neocomian time were almost synchronous with the intrusion of large granite plutons (Sakhanya and Syachan) into the fold-and-thrust structures in the northern part of the Verkhoyansk-Chersky orogenic belt. By the end of the Neocomian or in pre-Aptian time, strike-slip deformations of the second Late Mesozoic stage were superposed on the early thrust structures. At that time, the Selennyakh block was divided into smaller blocks by strike-slip faults, among them the Kalychan one. Two ore-bearing segments of different structure, Pologiy and Arbat, are distinguished within the Kalychan dextral strike-slip fault zone. As a result of strike-slip motions, the sedimentary rocks of these segments became steeply inclined, strongly deformed, and were pierced by a network of variably oriented fractures and cracks, which made them highly permeable for the circulating hydrothermal and ore solutions. The major Kalychan, Upper Kalychan and Arbat strike-slip faults are interpreted as the ore-feeding faults. The feathering subsidiary faults as well as strongly fractured zones are considered as ore-controlling and ore-bearing structures. The end of the Neocomian was marked by completion of the collision, and the Aptian-Albian period saw the inception of the Dzhakhtardakh volcanogenic belt of Early to Late Cretaceous age. Its formation is considered to be related to the crustal extension processes preceding the opening of the Eurasian ocean basin.

1. Introduction
The Sakandzha ore district occurs in the north-western margin of the Selennyakh allochthonous block of the Omulevka terrane forming part of the Kolyma-Omolon microcontinent [1]. It is made chiefly of the Lower to Middle Paleozoic miogeoclinal carbonate and clastic-carbonate rocks. The Selennyakh block is bounded on the west and north by the Nalchan and Polousny thrusts, respectively, on which its Paleozoic strata are displaced northward to cover the Mesozoic clastic rocks of the Tuostakh-Polousnyi fold belt. On the southeast, the block borders the Talyndya strike-slip fault system on which it comes in contact with the Late Jurassic effusive rocks of the Syachan zone of the Uyandina-Yasachnaya volcanic belt. The fold and thrust structures of the Selennyakh block are intruded by granite plutons of the Northern batholith belt and dolerite dikes of Late Mesozoic age.
Figure 1. Tectonic map of the Pologiy and Arbat deposits area, Sakandzha ore district (A) and sketch map of NE Asia showing studied location (black rectangular) (B):

Kolyma – Omolon microcontinent: PT – Prikolyma terrane, OT – Omolon terrane, O – Omulevka terrane, AT – Arga-Tas terrane, ZB – Zyryanka basin; Verkhoyansk Fold-thrust belt: PS – Polousnyi synclinorium, ID – In’yali-Debin synclinorium, WV – West Verkhoyansk; SAS – South Anyui suture. deposits: 1 – Ordovician, 2 – Silurian, 3 – Devonian; 4 – geological boundaries; faults: 5 – major (UK – Upper Kalychan, K – Kalychan, A – Arbat), 6 – minor, 7 – strike-slip fault, 8 – thrust fault; 9 – location of deposits: P – Pologiy, A – Arbat; 10 – structural profiles 1 – 1’, 2 – 2’ and 3 – 3’ (shown in Figure 2); on stereograms: figure – stereogram number; n – number of measurements.
2. Tectonic structures
The Pologi and Arbat gold deposits, forming part of the Sakandzha ore district, are located in the Inach-Nalchan-Sakandzha interfluve (figure 1). Tectonic framework of the study area was first described in the 50-60s of the last century. Geological survey conducted by L.A. Musalitin, M.A. Galkin, and G.S. Sonin revealed here the NE-oriented Kalyanch anticline disturbed along strike by the same name reverse strike-slip fault system. Later on the general tectonic pattern of the Sakandzha ore district was interpreted as a NW-vergent thrust sheet [2, 3, 4]. The results of detailed structural investigations conducted across the entire Selennyakh block area [2, 4, 5, 6, 7] clearly show that its tectonic units were formed mainly as a result of Late Mesozoic collisional events during two deformation stages: the early thrust and the late strike-slip ones. The occurrence of the Early Carboniferous thrusting in the area [3] is declared without presenting any evidence.

In our view, NW- and SE-trending zones of fold-and-thrust deformation separated by a system of strike-slip faults may be recognized within the Sakandzha ore district (figures 1, 2). Their structures are defined by major folds of the first deformation stage: the Ukhtav syncline and the Kalyanch anticline, respectively. These folds are faulted and separated by dextral strike slips of the Kalyanch fault zone formed during the second Late Mesozoic deformation stage. The tectonic pattern of the area was determined on the basis of data from geological survey, direct geological-structural observations, and measurement of bedding orientation in different sections of the study area, which are presented in the circle stereograms (lower hemisphere projection, Wulff stereonet) in figure 1. The early folds inferred in the Ordovician rocks of the Kalyanch and Arbat faults with uncertain relations to the late F_{n+1} and F_{n+2} folds are beyond the scope of this study.

3. Ukhvat syncline
Exposed in the study area are its NW limb and a trough with a total width of about 12 km (figures 1, 2). The SE limb of the fold is faulted by longitudinal strike slips of the Kalyanch fault system.

In the upper reaches of Pologi, Inach, and Vilka creeks, the limb of the syncline is composed of Middle-Upper Ordovician and Silurian rocks. Fragments of its trough are preserved in the Inach R. basin and headwaters of Kalyanch in the outcrops of the Lower Devonian rocks separated by faults. From northeast to southwest, the syncline narrows down to 1.5 km to get closed in the upper reaches of Krutoy creek. Here, a narrow centroclinal part of the syncline with the preserved SE limb is exposed, in which the Upper Silurian carbonate rocks in the middle reaches of Pologi creek plunge to NW at 45-85° (figure 1, stereogram 1, figure 2).

Farther north, in the headwaters of the Inach R. and in the river basin of Inarindzha, along the whole length of the NW limb of the syncline, the Upper Ordovician and Silurian rocks monoclinally dip to E-SE at 30-85° (figure 1, stereograms 2, 3). The opposite orientation of bedding seen on stereograms 2 and 3 corresponds to position of the NW limbs of small open and tight folds (1 m to several tens of meters wide) complicating the limb of the Ukhtav syncline (Pologi and Ukhtav headwaters). Inclinations of axial surfaces of small asymmetric folds indicate a northwestern vergence of the fold and thrust structures. This is further supported by the presence in the thrust zones of segments with strata overturned to NW at 45-60° (e.g., in the upper course of Vilka, the right-side tributary of the Inarindzha R.).
4. Kalychan anticline

Its NW limb is faulted by longitudinal strike slips of the Kalychan fault system. In the Pologiy creek basin, the strongly deformed Middle-Ordovician clayey-carbonate deposits of the core of the Kalychan anticline border the trough structures of the Ukhvat syncline along the Upper Kalychan fault (figures 1, 2).

The wide southeastern limb of the Kalychan anticline composed of the Middle-Upper Ordovician and Early Silurian carbonate rocks occurs along the left bank of the Sakandzha R. and its tributaries. In the southwest, in the lower reaches and the mouth of the Kalychan R., these rocks dip monoclinally to E-SE at 45-85° (figure 1, stereograms 4, 5). Northeasternly, in the Zvonkiy creek basin, the same rocks plunge to SE (figure 1, stereogram 6). At 4-5 km to the north of Zvonkiy creek, on the left bank of the Sakandzha river, the Ordovician rocks of the limbs of the Kalychan anticline rotate to have a nearly EW orientation (figure 1, stereogram 7).

The southwestern closure of the Kalychan anticline is noticed on the right bank of the Nalchan R. (downstream from the Sibichan R. mouth). On the left bank of the Nalchan R. between the Upper Kalychan and Kalychan faults, a periclinal part of the anticline is observed. The Ordovician rocks dip to the E-SE, S-SW and W-SW at 35-65° (figure 1, stereogram 8). In folding and thrusting, wide periclinal closures are normally typical of large antclinal ramp folds.

Figure 2. Geological-structural profiles across the Pologiy and Arbat segments of the Kalychan strike-slip fault zone:

Deposits: 1 – Ordovician, 2 – Silurian, 3 – Devonian; 4 – structural lines; 5 – strike-slip fault, 6 – thrust fault, 7 – zones of the Pologiy and Arbat segments; faults: UK – Upper Kalychan, K – Kalychan, A – Arbat. Position of profiles 1 – 1', 2 – 2' and 3 – 3' is shown in figure 1.
Small-scale folds, complicating the SE limb of the Kalychan anticline, are well seen in outcrops in the lower reaches of Zvonkiy creek. These are ramp or decollement folds in the zones of bedding-plane thrusts (figure 3, A). Noteworthy are up to 10 km wide zones of small folds with steeply dipping (55°-85°) axial planes accompanied by cleavage (figure 3, B). The folds are, in most cases, associated with both the bedding-plane and different-scale cross-cutting thrusts.

Large bedding-plane thrusts are often restricted to the contact zones of sedimentary strata with contrasting competence, e.g., to the zones of the upper and lower boundaries of the Lower Silurian carbonate-clay rocks of the Ukhvat Fm. over- and underlain by the Upper Ordovician and Upper Silurian massive carbonate rocks, respectively.

5. Kalychan strike-slip fault zone.
The structural framework of this extensive linear zone up to 1-2 km wide is defined by strike-slip faults of the second deformation stage (figure 1). The most important of them is the Kalychan (Central) dextral strike-slip fault of north-east trend which bifurcates into two branches: the Upper Kalychan and Arbat faults. The Kalychan zone is subdivided into two segments: the southwestern Pologiy segment and the northeastern Arbat segment (figures 1, 2).

5.1. Pologiy segment
This wedge-like segment is made of the Middle Ordovician intensely deformed clayey-carbonate rocks forming the NW limb of the Kalychan anticline (figure 2). In the southeastern wall of the Upper Kalychan fault, the Ordovician clayey-carbonate rocks dip subvertically (85-90°), following the NE trend of the fault (figure 1, stereogram 9). The clay beds up to 20-35 m thick with thin interlayers of carbonate rocks are foliated parallel to bedding.

Farther south we observed a structurally similar wide (500 m) fault zone with ore bodies and disintegrated fragments of mafic dikes up to 4 m thick. Also found here are morphologically various small folds of different generations.

On the left bank of Pologiy creek, in the Upper Kalychan fault zone there are found two fragments of a broken mafic dike (figure 4, A). Upstream of the creek, on the NW wall of the Upper Kalychan fault there are traced subvertical Silurian organogenic carbonate deposits of the SE limb of the Ukhvat syncline.
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Figure 4. Tectonic structures of the Pologiy segment of the Kalychan strike-slip fault zone (Pologiy creek):

A – Upper Kalychan (VK) fault zone, in the foreground are fragments of dolerite dikes (d). Structures of the second deformation stage: B – tight fold $F_{n+2}$ with a deformed pre-strike-slip calcite vein (q).

In the lower course of Pologiy creek, between the Upper Kalychan and Kalychan faults, there occur variously-oriented sedimentary rocks inclined at 70-90° toward N and S (figure 1, stereogram 10). In adjacent fold-and-thrust zones, the Ordovician-Silurian deposits have a differing NE trend (figure 1, stereograms 2, 3, 4-6). Strike-slip faults with the accompanying folds are the dominant type of deformation in the segment.

Also, the earlier fold-and-thrust deformations in this segment are superposed by the late strike slips faults. Folds of the first generation, sometimes with the axial plane cleavage, are preserved but they are overturned, with their axes inclined steeply (up to vertical). That’s why it is often difficult to differentiate between the early and late folds, except in clear cases when isoclinal folds of the early generation ($F_{n+1}$) with horizontal hinges are draped into open folds of the late generation ($F_{n+2}$) with vertical hinges or when typical strike-slip-related open and tight folds ($F_{n+2}$) with steep axes are observed (figure 4, B).

In another site of the Pologiy segment, in the Kalychan R. area, in the mouth of Bolotny creek between the Upper Kalychan and Kalychan faults there is a zone of exposed minor strike slips. Here the rocks dip steeply mainly to the SW and W (figure 1, stereogram 11). They are faulted by numerous cross-cutting low- and high-angle faults and fractures with slickensides of different kinematics. Low-amplitude (up to 1 m) conjugate strike slips are clearly seen. Folds of two generations are also present.

5.2. Arbat segment
In this rhomb-shaped segment, monoclinally dipping rocks of Middle-Upper Ordovician to Lower Devonian age are exposed (figures 1, 2). This suggests the presence here of a fragment of the trough of the Ukhvat syncline, which was detached and displaced southward along the Kalychan strike-slip fault. It seems likely that during this motion the sedimentary rocks acquired subvertical (70-90°) orientation. The strike of the rocks changes from NE to NS to NW from south to north (figure 1, stereograms 12, 13).

The structure of the Arbat segment is largely defined by longitudinal and transverse strike-slip faults (figure 1). The longitudinal faults tend to occur at the contacts of sedimentary strata with contrasting competence, e.g., at the contacts of carbonates of the Ryabina Fm. with clay-carbonates of the underlying Ukhvat Fm. and red beds of the overlying Artyk-Yuryakh Fm. (figure 5, A). These faults seem to have formed already at the early fold-and-thrust deformation stage. At the late stage of deformation, they assumed subvertical orientation.
Figure 5. Fault structures of the second deformation stage in the Arbat segment of the Kalychan strike-slip fault zone:

A – bedding-plane faults (dashed line) between the Ukhvat (S_{uh}), Ryabina (S_{rb}) and Artyk-Yurakh (S_{ar}) Fms. (in the foreground is the left slope of Arbat creek), B – cross-cutting fracture system (along hammer) in bedrock’s outcrops of Arbat creek, C – en-echelon extension fractures, D – stripped-off fragment of carbonate layer transferred by a strike-slip fault (bedrock’s outcrops of Zvonkiy creek).

The transverse faults are represented by dextral and sinistral strike-slip faults which are marked by a series of streams. The amplitude of horizontal displacement on some of them attains 100 m. The faults are accompanied by zones of crushing and fracturing. The closely spaced fractures (figure 5, B) have NW and EW orientation. There are en-echelon-arranged calcite veins defining shear zones characterized by strike-slip kinematics (figure 5, C, D).

In the west of the segment, in the Kalychan fault zone (Inach R. basin), the strike-slip deformations are manifested in different-aged sedimentary rocks where they are superposed on the earlier fold-thrust structures. Here we observe areas both of mildly deformed monoclinally dipping rocks and of intensely manifested folds of two generations (figures 6, 1, stereogram 14). The dolerite dikes up to 25 m thick are seen to have been displaced on the NE-trending dextral strike-slip faults.

Outside of the Arbat segment, intense strike-slip deformations are noticed in the area of the eastern branch of the Arbat fault (figure 1). Badly deformed Ordovician rocks and mafic dikes as well as numerous calcite veins are found here. An example of such strike slips is shown in (figure 5, D).
Figure 6. Examples of relationship between folds of two generations in the Kalychan strike-slip fault zone (Arbat segment) manifested in incompetent rocks of the Lower Silurian Ukhvat Fm. exposed along the Inach R. banks (A – D).

Table 1. Paleostress axes.

| Observation points | $n$ | Paleostress axes dip |
|--------------------|-----|----------------------|
|                    |     | Tension (1)          |
|                    |     | Intermediate (2)     |
|                    |     | Compression (3)      |
|                    | Azimuth | Azimuth | Azimuth |
| Pologiy (strike-slip) | 93  | 204.2 | 49.0 | 298.5 | 3.7 | 31.7 | 40.8 |
| Arbat (all faults)   | 78  | 328.9 | 12.8 | 140.5 | 77.0 | 238.4 | 1.8 |
| Arbat (strike-slip)   | 59  | 327.8 | 19.0 | 138.1 | 70.7 | 236.8 | 3.0 |
| Arbat (thrust and reverse) | 13 | 152.1 | 23.7 | 309.7 | 64.6 | 58.2 | 8.6 |

Stress field restoration is based on measurements of fault surfaces and orientation of striae on the slickensides. Using the software given in [8] we estimated P (compression) and T (tension) axes (table 1). Studies of conjugate dextral and sinistral strike-slip faults in the Pologiy segment showed that the compression axis has a NW-SE orientation. Analysis of orientation of reverse strike-slip faults, normal
strike-slip faults, and thrusts revealed a similar direction of the compression axis (figure 7, A). In general, orientation of the compression and tension axes determined for the deformed strata in the Kalychan fault zone correlates well with the type model for a dextral strike-slip fault [9] (figure 7, B).

**Figure 7.** Calculation of orientation of principal stress axes (A) and main structures (B):

Stereograms of arcs of the great circle with calculated compression and extension axes: P – Pologiy segment – for left- and right-lateral strike slip faults; Arbat segment: A – for all fault types; As – for all strike slips and their combinations with other fault types, At – for thrusts and reverse faults. Lower hemisphere projection. Attitude elements of faults and striation on slickensides are used. n – number of measurements. Subscript index: 1, 2, 3 – tension, intermediate and compression paleostress axes, respectively. E – orientation of main structures in the dextral strike-slip fault zone after [9]; Symbols: C – compression axes, E – extension axes, N – normal faults, T – thrusts, R, R’ – Riedel shears (synthetic and antithetic faults), V – extension fractures, F – fold axes.

6. Discussion and conclusions

Thus, two ore-bearing segments of different structure, Pologiy and Arbat, are distinguished within the Kalychan dextral strike-slip fault zone (figures 1, 2). As a result of strike-slip motions, the sedimentary rocks of these segments became steeply inclined, strongly deformed, and were pierced by a network of variably oriented fractures and cracks, which made them highly permeable for the circulating hydrothermal and ore solutions. The major Kalychan, Upper Kalychan and Arbat strike-slip faults are interpreted as the ore-feeding faults. The feathering subsidiary faults as well as strongly fractured zones are considered as ore-controlling and ore-bearing structures.

The age of the studied deformations was determined as Early Cretaceous.

Southward from the study area, on the left bank of the Selennyakh R., the southwestern part of the Selennyakh allochthonous block is intruded by two large Early Neocomian granite plutons – Sakhanya and Syachan. The former is aged at 146-136 (Rb-Sr) and 142-136 (40Ar-39Ar) Ma, and the latter at 133-126 (Rb-Sr) and 136-134 (40Ar-39Ar) Ma [10, 11]. The crystallization age of the Sakhanya pluton is estimated at 140±2 Ma (U-Pb, zircons). Northeasterly (left bank of the Uyandina R.), the zone of junction of the Selennyakh block and the fold structures of the Tuostakh anticlinorium is unconformably overlain by the rocks of the Dzhakhktardakh volcanogenic field with the Aptian-Albian effusive-sedimentary strata at the base [10]. The aforementioned magmatic events show good temporal correlation with the final stage of the Late Mesozoic collision of the Kolyma-Omolon microcontinent with the eastern margin of the North Asian craton and with the formation of the Main and Northern granitoid belts [1, 12].

Formation of the fold-and thrust structures of the early Late Mesozoic deformation stage within the Selennyakh block and its thrusting, in the form of a thrust sheet, over the fold structures of the Tuostakh-Polouzny zone in Neocomian time was almost synchronous with the intrusion of large granite plutons (Sakhanya and Syachan) into the fold-and-thrust structures in the northern portion of
the Verkhoyansk-Chersky orogenic belt. By the end of the Neocomian or in pre-Aptian time, strike-slip deformations of the second Late Mesozoic stage were superposed on the early thrust structures. At that time, the Selennyakh block was divided into smaller blocks by strike-slip faults, among them the Kalychan one. The end of the Neocomian was marked by completion of the collision, and the Aptian-Albian period saw the inception of the Dzhakhtardakh volcanogenic belt of Early to Late Cretaceous age. Its formation is considered to be related to the crustal extension processes preceding the opening of the Eurasian ocean basin [1].

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