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GEOLOGY

Structural–Dynamic Factors of Magma and Ore Genesis in the East Sikhote Alin Volcanoplutonic Belt

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The East Sikhote Alin volcanoplutonic belt (ESAB) formed in the Albian–Paleocene. Magmatism and metallogeny in this belt were related to activation of Sikhote Alin strike-slip faults [4, 7]. Deep NNE-trending strike-slip zones control tin, tungsten, base metal, and gold deposits. At the same time, areas of dispersed ore mineralization up to 10 km wide are observed between these strike-slip zones. Their structural–dynamic nature and geodynamic settings of Cenomanian–Cenozoic magmatism, which produced the volcanic cover of the belt, remain unclear thus far. We investigated this issue in the Samarga ore district, which represents a large ESAB fragment located in the northeastern Primorye region [1]. We also analyzed results of structural investigations [2] conducted during additional geological investigation of the region by the Primorye prospecting–mapping expedition [1]. It is established that NW-trending zones of ore mineralization are controlled by extension structures of the continental crust related to strike-slip faults that served as the main magma conduits during the formation of the ESAB volcanic cover in the Cenomanian–Paleocene.

The Samarga ore district is characterized by all structural features typical of the ESAB, in particular, lateral latitudinal (W–E) lithotectonic and chronological zoning (Fig. 1). The chronological zoning reflects the vertical structure of a belt that was inclined southeastward in the Neogene and then exhumed by oblique erosion [4, 5, 7]. The oblique erosional surface recovered different levels of the belt, including the Early Cretaceous folded basement of the volcanic cover crosscut by NE-trending strike-slip zones (Fig. 1) that were appreciably active in the Late Cretaceous [3, 7]. The less distinct manifestation of strike-slip faults in the volcanic cover is attributed to their multiple overlapping by volcanics in the Cenomanian–Paleocene. At least four magmatic stages can be distinguished in the vertical structure of the belt within the Samarga ore district [1]. The lower level (Cenomanian stage) is represented by granitoid bodies localized in the Early Cretaceous basement (Fig. 1). Next, the Coniacian–Turonian stage is marked by the formation of the widespread Primorye Formation composed largely of acid volcanics unconformably overlying the folded basement. In the Maestrichtian, the Primorye Formation was intruded by small gabbro and gabbrodiorite bodies and large comagmatic volcanics (Samarga Formation of largely intermediate composition). In the Danian and subordinate Paleocene, the volcanic cover was injected by numerous complex intrusions (from granites to gabbro) accompanied by their comagmatic volcanics (Kyum Sequence, Bogopol Formation).

From the point of view of geodynamics, the causes and succession of magmatism should probably be attributed to activation stages of the NE-trending strike-slip faults. Noteworthy is the fact that intrusions and ore mineralization are closely associated and localized in NW-oriented structures (Fig. 1). Relative to strike-slip faults, these structures are characterized by transverse orientation bordered by strike-slip faults that were active synchronously with Late Cretaceous magmatism. Therefore, such structures may be considered as parageneses of faults that served as the main magma-conducting extension structures (hereafter, magma conduits). The pulsating activation of strike-slip faults determined the repeated opening of these magma conduits. In the Povelitsa structure (Fig. 1), for example, these processes resulted in the successive formation and overlapping of Late Cretaceous volcanic stages composed of various lavas and tuffs (Fig. 2). In contrast to lower stages, the upper stage (rhyolites and felsites) is substantially eroded. Its magma conduits represented by a system of multiphase largely rhyolite porphyry dikes up to 100 m thick are locally exhumed (Fig. 2). Complete erosion of Danian–Paleocene volcanics in this area resulted in the exposure of extension structures (magma conduits) compensated by basaltic

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Fig. 1. Structural–dynamic control of magmatism and ore mineralization in the Samarga ore district (northeastern Primorye). (*1*) Miocene basalts; (*2*) Late Cretaceous (Cenomanian–Danian) acid and intermediate volcanics; (*3*) folded basement of the volcanic cover (Aptian–Albian largely terrigenous complexes); (*4, 5*) Cenomanian granites, granodiorites, diorites (*4*) and their cryptoplutons represented at the surface by contact hornfels fields (*5*); (*6*) Maestrichtian gabbro and gabbrodiorites; Danian granites, granodiorites, and gabbro; (*7*) separate strike-slip faults (dashed lines designate inferred fractures) of strike-slip fault zones: (A) Adin, (T) Topograficheskaya, (K) Kilou, (S) Skalistaya, (B) Burmatov, (P) Povelitsa, (E) Edinka; (*8–12*) types of mineralization from high-temperature (*8*) to relatively low-temperature (*12*) (based on lump and furrow sampling data): (*8*) mainly tungsten, (*9*) mainly tin, (*10*) base metal, (*11*) gold–silver with base metals, (*12*) gold–silver; (*13*) magma-conduits: (P) Povelitsa, (V) Venyukovka; (*14*) extension structure superimposed on Cenomanian granitoids of the first opening stage of the Venyukovka magma conduit; (*15*) attitude elements of Lower Cretaceous sedimentary layers; (*16*) fragment of the Povelitsa magma-conduit (2) and gold–silver deposits: (3) Burmatov, (4) Yagodnoe (numerals correspond to figure numbers).

andesite, dioritic porphyry, and other dikes that crosscut the entire pre-Danian volcanic complex.

The synkinematic opening stages of magma conduits are reflected in the succession of different types of magmatism in the Venyukovka structure, which has been studied best (Fig. 1). The initial (Cenomanian) stage was marked by formation of the extension structure in an 8-km-wide block of Lower Cretaceous rocks sandwiched between the Burmatov and Skalistaya strike-slip fault zones. This structure, up to 12 km wide and transverse relative to strike-slip faults, was favorable for the generation of magmas (decompression effect) and the vertical migration of magmas and fluids. Frontal (lowest temperature and viscous) granitoid magmas crystallized at shallow depths and plugged the structure. The magma chamber probably continued to function beneath the granitoid plug, which resulted in magma differentiation. Numerous (largely, NW-striking) dikes of different compositions crosscut the Cenomanian granitoids, indicating new stages of opening of the Venyukovka magma conduit. One of the widest (3 km) extension structures divided the granitoid plug into two parts (Fig. 1). The multistage opening of this superimposed structure is reflected in the formation of NW-trending extrusive bodies parallel to boundaries of the structure. The composition of successively formed bodies is identical or close to that of reliably dated rock complexes. Therefore, we can outline the following lithochronological stages of magmatism (and, consequently, structure opening): rhyolites and felsites (Turonian–Coniacian); dacites and andesites (Maestrichtian); granite porphyries and granites (Danian–Paleocene).

Thus, the Venyukovka magma conduit opened at least four times during the Late Cretaceous–Paleocene. This was likely accompanied by the opening of other similar structures, which explains the regional (not local) development of volcanogenic complexes. The compositional variation of volcanics probably reflects the exhumation of differentiates of long-lived magma chambers. At the same time, intermediate chambers could probably form at different levels of the magma conduit. The magma composition in such chambers was determined by its migration through the conduit and (or) lithology of the host continental crust.

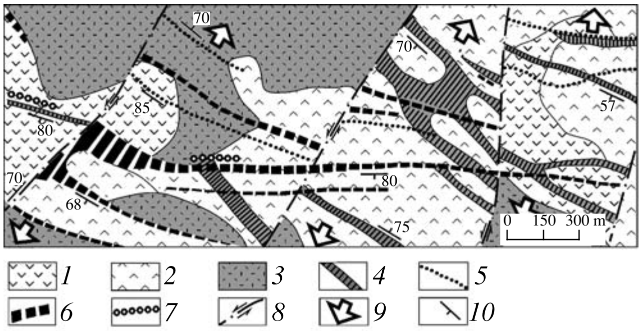

Fig. 2. Succession of the opening of magma conduits in the Povelitsa extension structure (fragment). (*1–3*) Successive volcanic stages: (*1*) lower stage (andesites and lava breccia), (*2*) middle stage (dacites, dacite porphyries, and dacite tuffs), (*3*) upper stage (rhyolites and felsites); (*4–6*) successive opening of magma conduits: (*4*) Late Cretaceous, (*5, 6*) Danian–Paleocene basaltic andesite dikes; (*7*) orebodies; (*8*) strike-slip faults; (*9*) extension direction; (*10*) orientation of fractures and dikes.

Intrusive bodies localized in the magma conduits are characterized by vertical contacts. Gravity minimums mark their steep dip to depths of 15–20 km [1]. These depths are close to the maximal thickness (up to 15 km) of the Lower Cretaceous (Berriasian–Albian) Sikhote Alin sedimentary sequence with Albian granitoid magmatism widely developed at the lower (Berriasian–Valanginian) level and beneath this level [5, 7]. Prior to the Cenomanian, the Lower Cretaceous sequence overlapped the synsedimentary deep-seated strike-slip faults and served as a structural screen for ascending magmas and fluids that transformed terrigenous sediments into granitoids. This process fostered the development of numerous large and flat granitoid bodies at the lower levels of the screening sequence. The northeastern strike of most Albian granitoid bodies is conformable with the Sikhote Alin system and indicates the development of magma chambers in cores of brachyanticlines that played the role of cryptic decompression chambers favorable for localization of deep fluids and magma generation [7]. By the Cenomanian, the Lower Cretaceous sequence was crosscut simultaneously with the synkinematic folding by a system of NE-trending sinistral strike-slip faults. Together with the magma conduits, the faults penetrated the active Albian magma chambers. These processes promoted the intermittent and long-term (Cenomanian–Paleocene) ascent of magmas to the surface and the formation of the volcanic cover.

The Albian magmatism was probably the main source of ore-bearing fluids. This assumption is supported by two facts [5, 7]. First, only scarce ore mineralization is developed and ore deposits are absent below this level. Instead, scattered mineralization is widespread and practically all ore deposits of Sikhote Alin are localized at and above this level. Second, ore mineralization is characterized by vertical composition and temperature zoning from the tungsten and cassiterite–quartz associations to the cassiterite–silicate, cassiterite–sulfide, and lead–zinc associations. Similar to the central Sikhote Alin, the vertical zoning in the Samarga ore district is crowned by low-temperature gold–silver mineralization (Fig. 1). It is conceivable that the long-term development of Albian magma chambers fostered the differentiation of magmas and separation of the ore-bearing fluid phase. Ascent of this fluid was accompanied by the successive precipitation of ore mineral associations depending on *PT* conditions at different levels of the crust.

The magma conduits were highly permeable at the opening stage. The fluid flow with high migration characteristics penetrated along numerous differently oriented channels, which resulted in dispersion of ores and formation of ore mineralization zones (Fig. 1). However, ore concentrations usually did not reach the level of deposits. Deep strike-slip fault zones, which represent compression structures, had quite different structural–dynamic characteristics. Conditions of compression in the strike-slip zones are mainly favorable for the opening of the vertical system of fissures that are parallel to the middle and maximal stresses of the strike-slip deformation ellipsoid (NNW-trending extension fractures in the case of sinistral strike-slip faults), while other fissures remain closed. Such patterns are very favorable for both vertical migration of fluids and ore concentration [4, 6, 7]. This fact explains the control of ore deposits by strike-slip fault zones in the central and southern Sikhote Alin regions [3, 4, 6, 7]. The above statement is also confirmed in the Samarga ore district (Fig. 1), where structures and formation dynamics of gold–silver deposits confined to strike-slip fault zones in sedimentary and volcanogenic sequences of different ages and compositions were studied in detail (Fig. 1).

The Burmatov deposit located in the synonymous strike-slip fault zone (Fig. 1) is developed in the Aptian–Albian deformed and largely terrigenous sequence (Fig. 3). In this area, one can see the main magma-conducting level of the Upper Cretaceous volcanic cover. Magma conduits filled with rhyolite porphyry dikes (up to 0.5 km thick) represent synkinematic extension structures. The NNW-oriented orebodies reflect the post-dike pulse of the opening of extension structures in response to activation of sinistral movements in the strike-slip fault zone.

The Glinyanoe deposit is also located in the Burmatov strike-slip fault zone south of the Burmatov deposit. It is located, however, at a higher level in the Late Cretaceous volcanic cover. Subordinate strike-slip faults of the zone crosscut the volcanic rocks. Orebodies are NNW-oriented similarly as in the Burmatov deposit, i.e., obliquely to the strike-slip fault zone, which implies opening of ore-hosting extension fractures in response to postvolcanic activation of sinistral strike-slip faults.

The Yagodnoe deposit (Fig. 1) is located in a Danian granodiorite massif (Fig. 4). Orebodies form echelon

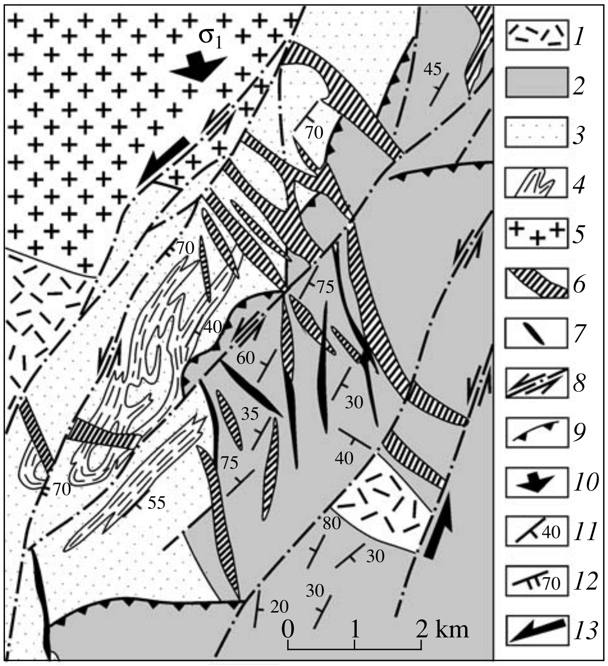

Fig. 3. Geological–structural map and dynamic–kinematic formation settings of the Burmatov deposit. (*1*) Late Cretaceous acid volcanics; (*2, 3*) folded basement of the volcanic complex: (*2*) middle–upper Albian (terrigenous, volcanogenic, and volcanogenic–terrigenous rocks), (*3*) lower Aptian–middle Albian (largely terrigenous rocks); (*4*) cores of anticlines composed of siltstones; (*5*) granites (Cenomanian); (*6*) rhyolite porphyry dikes; (*7*) orebodies; (*8*) strike-slip faults; (*9*) thrusts; (*10*) direction of regional compression; (*11, 12*) orientation of layers and tectonic planes, respectively; (*13*) direction of displacements along the Burmatov strike-slip fault zone.

chains morphologically corresponding to the structure of potential sinistral strike-slip faults. The echelon of extension fractures is frequently developed in overlying rocks that are intensely reworked by strike-slip faults. They reflect last pulses in activation of deep strike-slip faults.

Thus, we can make the following inferences. The Late Cretaceous–Paleocene activation of NE-trending sinistral strike-slip faults determined the formation of their structural parageneses (transverse extension structures, which served as the main magma conduits). Multiple opening of these conduits resulted in the successive formation of volcanic complexes. The long-term influx of ore-bearing fluids promoted the formation of dispersed mineralization within the volcanic complexes. Ore deposits are largely controlled by deep strike-slip fault zones, the structural–dynamic properties of which were favorable for the ascent of fluid flows and concentration of ores.

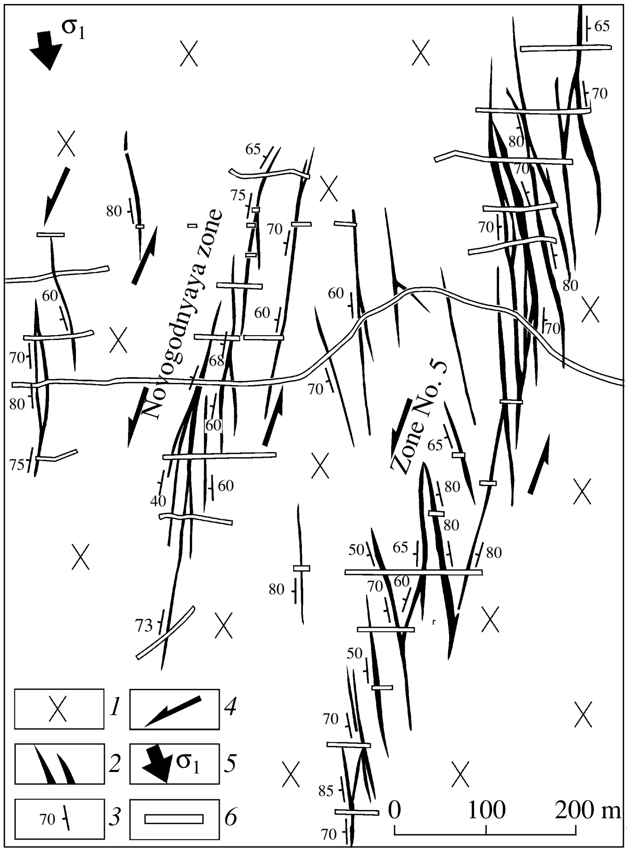

Fig. 4. Structural–dynamic formation settings of the Yagodnoe deposit. (*1*) Granodiorites; (*2, 3*) orebodies and their orientation, respectively; (*4*) direction of displacements with the formation of potential strike-slip faults; (*5*) regional compression direction; (*6*) exploration trenches.

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