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DISCUSSION

Authigenic Minerals in Phanerozoic Volcanosedimentary Deposits of the Northern Part of the Asian Continent–Pacific Ocean Transition Zone[1]

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Abstract—Authigenic minerals have been studied in Phanerozoic volcanosedimentary deposits in the northern part of the Asian continent–Pacific Ocean transition zone. The following were found: chlorite, mica, corrensite, rectorite, defective chlorite, kaolinite, smectite, calcite, barite, gypsum, epsomite, zeolites, cristobalite, quartz, and goethite. The minerals corrensite and rectorite have significant indicative properties, as do the assemblages corrensite–laumontite, corrensite–epsomite–authigenic calcite and mica–kaolinite–quartz. Such a range of minerals indicates that the thickness of sediments in the studied basins could reach 3–5 km, and their formation temperature could be more than 150°C. The mica–kaolinite assemblage may indicate epicontinental sedimentation conditions associated with coal formation on nearby land, the corrensite–chlorite assemblage may indicate conditions favorable for the evaporation of seawater, and the presence of laumontite in it may indicate periodic calcium supply to the sedimentary basin. The periods of mineral formation, possibly associated with global climatic events, have been identified: 113–120, 110–113, 105–110, 93–95, 72–83, 61–72, 56–61, 33–56 Ma, which can serve as benchmarks to determine sedimentation conditions and the framework for more reliable stratigraphic constructions.

Keywords: Phanerozoic deposits, authigenic minerals, transition zone, sedimentation conditions

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INTRODUCTION

The alteration of matter in the Asian continent–Pacific Ocean transition zone is of not only purely scientific, but also practical interest, since huge mineral resource reserves are concentrated in this zone. There are a large number of studies spanning the age range from the Paleozoic to the present, but mineralogically the rocks and sediments of this period are much less characterized, especially from the viewpoint of authigenesis (Kurnosov, 1975, 1982; Chudaev, 1977, 1978; Volokhin, 1980, 2012; Markevich, 1985; Koporulin, 1992, 2006). The author of this article has accumulated extensive factual material that can partially fill this gap by summarizing the data obtained. Authigenic minerals, being sensitive indicators of sedimentation conditions, indicate changes in the paleogeographical environment and the nature of dia- and epigenetic alteration of sedimentary material. Layered silicates (smectite, corrensite, rectorite) and zeolites have the most pronounced indicative features, which can serve as reference points for recreating the physicochemical and climatic sedimentation conditions and also form the basis for more reliable stratigraphic constructions.

MATERIALS AND METHODS

The material for the study comprised samples of volcanosedimentary rocks selected by the author during field surveys in Primorsky krai, during coastal expeditions on the Sakhalin (Terpeniya Peninsula) and Shikotan islands in 2000–2009, recovered during underwater dredging in the Sea of Japan and on the underwater Vityaz Ridge. As additional data, we used data on the Kamchatka Peninsula (the western part is the Palansky section and the eastern part is the Il'pinskiy Peninsula) (Fig. 1).

The main volume of samples (more than 1000) was taken on land (Southern Primorye) from volcanosedimentary and sedimentary rocks of a wide age range: from the Early Permian to the Miocene. Mainly conglomerates, sandstones, and tuffaceous sandstones, sometimes mudstones, silty mudstones, and tuffaceous mudstones were sampled. Samples were taken from natural coastal outcrops of the Sea of Japan, rivers, and streams, as well as artificial quarries and along

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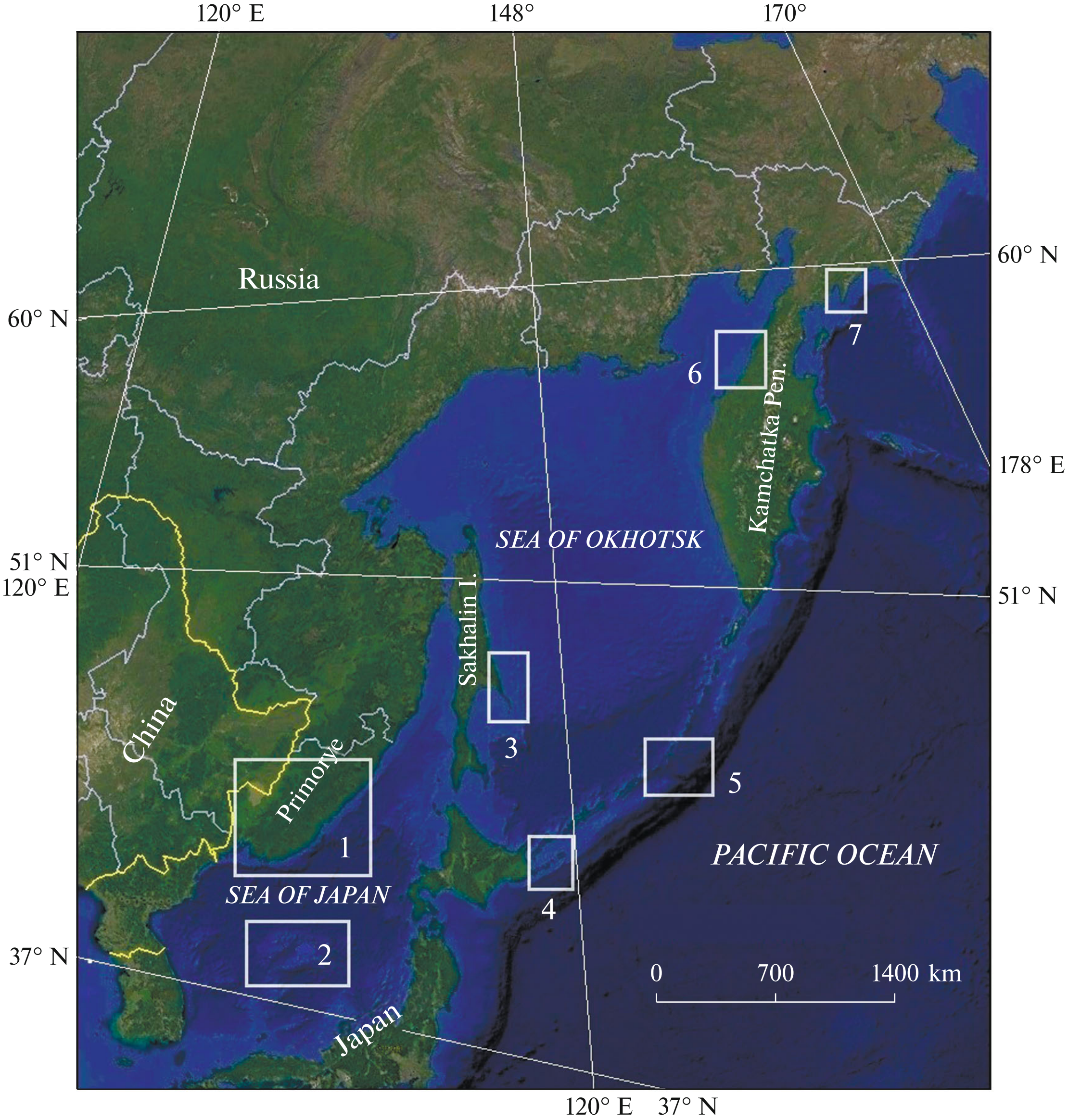


Fig. 1. Simplified map of studied area. 1, Primorye region; 2, Yamato Rise; 3, Terpeniya Peninsula; 4, Shikotan Island; 5, underwater Vityaz Ridge; 6, Palana district; 7, Il'pinskiy Peninsula.

highways according to a geological map (Kutub-Zade et al., 2013). The author sampled deposits of the Pospelovskaya (Lower–Middle Permian) Formation; the Ostrovorusskaya Group (Lower–Middle Triassic) near Vladivostok, the Bogatinskaya Group (Upper Triassic) near the village of Zanadvorovka; the Chiganovskaya (Upper Jurassic–Lower Cretaceous) Formation near Bolshoy Kamen; the Taukhinskaya Formation and Primorskaya Group of central Primorye; the Korkinskaya (Lower–Upper Cretaceous) Group near the village of Lukyanovka; the Nikanskaya Group (Lipovetskaya Formation, Lower Cretaceous) near Cape De-Friz, Sokol Bay (Vladivostok), and Zanadvorovka; the Nikanskaya Group (Lipovetskaya, Galenkovskaya formations, Lower Cretaceous) near Cape De-Friz and Sokol Bay (Vladivostok); the Gladkinskaya (Lower Cretaceous), Nazimovskaya (Paleocene–Lower Eocene), Khasanskaya (Eocene–Oligocene), Kraskinskaya (Eocene), Klerkovskaya (Paleocene–Eocene), and Slavyanskaya (Miocene) formations of the Khasansky region; the Uglovskaya, Nadezhdinskaya, and Ust'davydovskaya formations of the Rechnoy Peninsula, near the village of Taurichanka; and the Ust'davydovskaya? Formation of the village of Romanovka (Mozherovsky, 2019, 2021a, 2021b, 2022).

In the Sea of Japan, the most studied rocks are of Early Cretaceous and Cenozoic age, established on the underwater Yamato Rise (North and South Yamato ridges), dredged from the slopes of the Primorye shelf and underwater volcanic edifices (Markov et al., 2009; Mozherovsky, 1986; Mozherovsky et al., 1983, 1989, 2001; Mozherovsky and Terekhov, 1991, 1998, 1999, 2016) (about 500 samples). On the Terpeniya Peninsula (Sakhalin Island), rocks represented by volcanic–siliceous deposits of the Kotikovskaya Group (Uchirskaya, Zaslonovskaya, Turovskaya, Ol'donskaya, and Limanskaya formations) were studied (Tsoy et al., 2005; Terekhov et al., 2010; Mozherovsky and Terekhov, 2016; Mozherovsky, 2022) (about 500 samples). On Shikotan Island, Cretaceous deposits of the Krabozavodskaya, Matakotanskaya, and Malokuril'skaya formations, as well as Cenozoic deposits of the Zelenovskaya and other formations were sampled (Palechek et al., 2008; Terekhov et al., 2011; Markevich et al., 2012; Mozherovsky and Terekhov, 2016; Mozherovsky, 2022) (about 300 samples). On the underwater Vityaz Ridge (region of the Kuril island arc), presumably Late Cretaceous (Maastrichtian–Danian?) and Cenozoic deposits were studied (about 200 samples) (Terekhov et al., 2012; Mozherovsky and Terekhov, 2016; Mozherovsky, 2022). Data were also used on the Campanian–Maastrichtian Palana section (Western Kamchatka), which are described in detail by (Palechek et al., 2003), and Cretaceous–Paleogene deposits of the Il'pinsky Peninsula (Eastern Kamchatka), studied by (Chudaev and Markevich, 1977, 1978, 1985).

The main method for studying mineral compositions is X-ray diffraction analysis. A Drone-2.0 diffractometer was used with CuK_α radiation (flat graphite monochromator), an anode voltage of 40 kV, and a current of 30 mA. Bulk samples of rock cement (<0.06 mm fraction), prepared by gravity sedimentation from an aqueous suspension, were studied in an air-dried state, saturated with ethylene glycol, and calcined at 550°C for 3 h. Diagnosis of mixed-layer formations was carried out in accordance with the models proposed in the work (Drits and Sakharov, 1976).

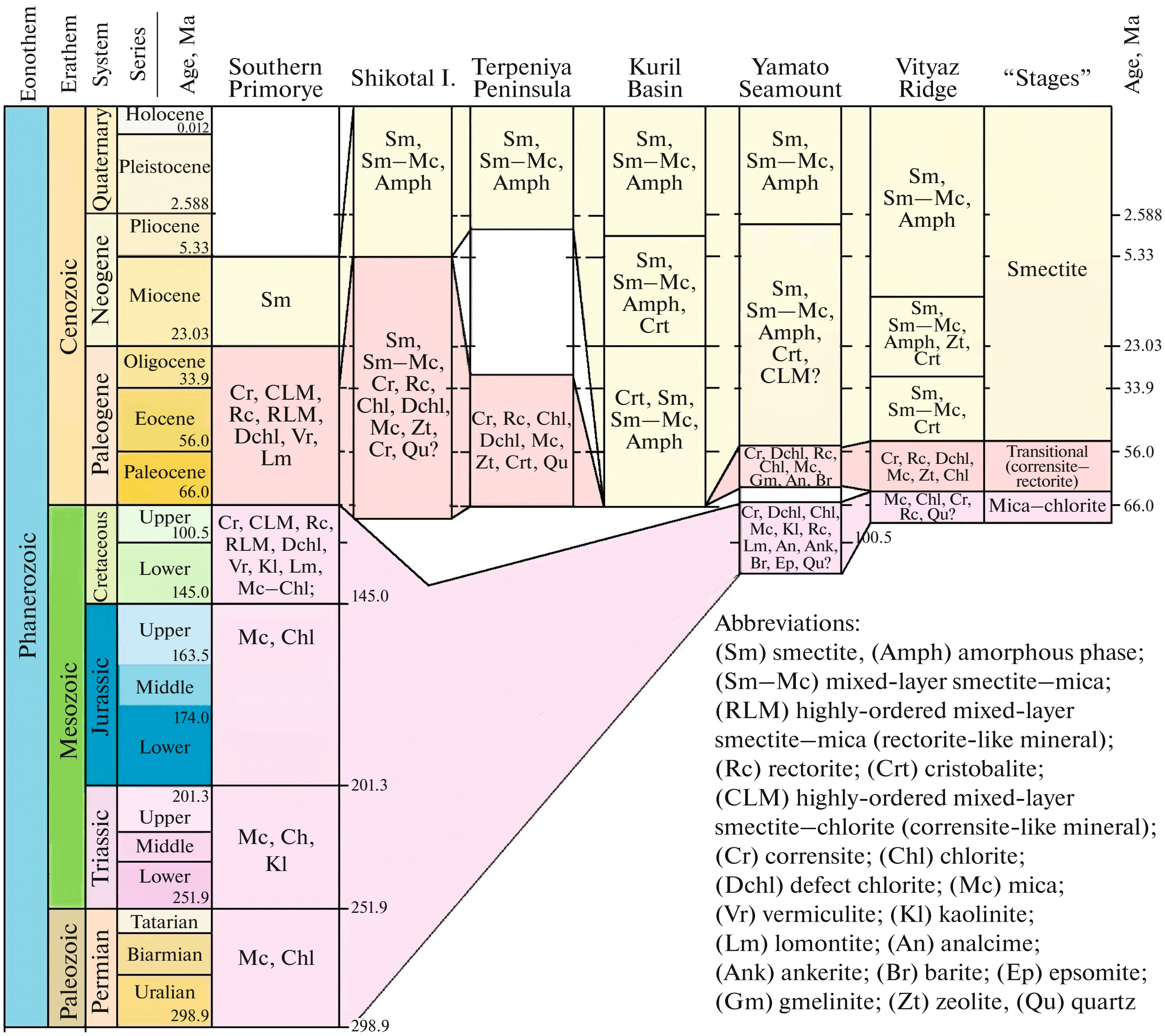
RESULTS AND DISCUSSION

The main authigenic minerals identified in Phanerozoic deposits of the northern Asian continent–Pacific Ocean transition zone are represented by chlorite, mica, corrensite, rectorite, and corrensite-like and rectorite-like varieties, defective chlorite, kaolinite, vermiculite(?), smectite, calcite, epsomite, barite, gypsum, laumontite, cristobalite. and quartz. Analcime, stilbite, ankerite, and goethite, which may be terrigenous in origin, have been identified in assemblages with them. Authigenic minerals from sediments of the southern and central parts of Primorye, Yamato Rise, Terpeniya Peninsula (Sakhalin Island), Shikotan Island, and the Vityaz Ridge (Fig. 2)—were studied. (Mozherovsky, 2019, 2021a, 2021b, 2022; Mozherovsky and Terekhov, 1991, 1998, 1999, 2016).

The most common mineral assemblages in the cement of Phanerozoic deposits of Southern Primorye are chlorite–mica (mica–chlorite) (mainly Permian, Triassic, Jurassic, Cretaceous), chlorite–corrensite (corrensite-like)–laumontite (Lower Cretaceous–Paleogene), mica–rectorite (rectorite-like) (Cretaceous–Paleogene), and mica–kaolinite–quartz (Triassic, Cretaceous). Mesozoic rocks of the Yamato Rise (Sea of Japan) are characterized by the mentioned assemblages, but the mineral composition is much richer. Here, in addition to those listed, epsomite, gypsum, barite, ankerite, and analcime were found (Mozherovsky and Terekhov, 1991, 1999; Terekhov et al., 2013, 2016). In Cenozoic (Paleogene–Neogene) deposits, the composition of mineral assemblages is somewhat poorer. Corrensite, corrensite-like, and rectorite-like formations have been noted (Vashchenkova et al., 2009; Mozherovsky, 2019). Zeolites in the general mineralogical section are distributed rather mosaically. Laumontite and analcime were found in the Early Cretaceous and Paleogene–Neogene, and stilbite, chabazite, and desmine are found in Upper Cretaceous and Paleogene deposits. The presence of corrensite in the studied Phanerozoic deposits was noted in the time intervals 113–120, 110–113, 105–110, 93–95, 72–83, 61–72, 56–61, and 33–56 Ma.

The most representative results of mineralogical analysis were obtained for Primorsky krai. Permian and Jurassic rocks of the region are characterized by mica and chlorite; Triassic rocks, by mica, chlorite, and kaolinite; Cretaceous rocks, by mica, chlorite, corrensite, mixed-layer mica–smectite type, kaolinite, defective chlorite, analcime, laumontite, stilbite, chabazite, quartz—index minerals of the analcime facies of epigenesis and, possibly, the laumontite facies. The probable depth of postsedimentary subsidence of Cretaceous rocks, based on mineralogical data, is estimated at 2–5 km (Coombs et al., 1959; Aoyagy and Kazama, 1980; Karnyushina, 1987).

The chlorite–mica (mica–chlorite) assemblage, reflecting the initial stage of metamorphism, is predominantly widespread in all formations from Permian to Lower Cretaceous and cannot be of indicative significance. The kaolinite–mica assemblage was found in the Triassic and Lower Cretaceous and is dated to the time of coal accumulation. For Lower Cretaceous rocks, the timing of its formation can be established as the Aptian–beginning of the Early Albian, 113–120 Ma (coal formation, "Lipovetskoe" time) noted for the Lipovetskaya Formation and Suchanskaya Group. The corrensite–chlorite assemblage is dated to the beginning of the Early Albian, 110–113 Ma (found in the Lipovetskaya and Galenkovskaya formations and in the Suchanskaya and Korkinskaya groups), and the corrensite–chlorite–lomontite assemblage, to the second half of the Albian, 105–110 Ma ("Galenkovskoe" time, which has been noted in the Galenkovskaya Formation and in the Suchanskaya and Korkinskaya groups). The retreat assemblage predominantly developed in the Late Cenomanian, 93–95 Ma ("Korkinskoe" time,



Abbreviations:
(Sm) smectite, (Amph) amorphous phase;
(Sm–Mc) mixed-layer smectite–mica;
(RLM) highly-ordered mixed-layer smectite–mica (rectorite-like mineral);
(Rc) rectorite; (Crt) cristobalite;
(CLM) highly-ordered mixed-layer smectite–chlorite (corrensite-like mineral);
(Cr) corrensite; (Chl) chlorite;
(Dchl) defect chlorite; (Mc) mica;
(Vr) vermiculite; (Kl) kaolinite;
(Lm) lomontite; (An) analcime;
(Ank) ankerite; (Br) barite; (Ep) epsomite;
(Gm) gmelinite; (Zt) zeolite, (Qu) quartz

Fig. 2. Authigenic mineral assemblages in Phanerozoic volcanosedimentary deposits of northern Asian continent–Pacific Ocean transition zone.

red-colored deposits of the Korkinskaya Group and Romanovskaya Formation) (Mozherovsky, 2021a, 2021b, 2022).

Thus, in the “Lipovetskian” time, we can distinguish two events for the kaolinite–mica assemblage, 113–120 Ma (the era of coal accumulation), and for the corrensite–chlorite assemblage, 110–113 Ma, a time comparable to an Early Albian event (Paquier event, OAE 1b, 111 Ma). For the “Galenkovskian” (presence of laumontite), the time interval can be determined as 105–110 Ma. The nearest global climatic events with a marked increased supply of calcium to sedimentary basins have been noted at the boundaries of 103, 105 Ma, and Urbino, 107.5 Ma (OAE1c? and OAE1d?) (Jenkyns, 1980, 2010). This recurrence can be explained by several periods of calcium supply to sedimentary basins and has not yet been sufficiently studied for these sediments. The formation interval of reedbeds of the Korkinskaya Group (upper part of the Romanovskaya Formation) 93–95 Ma (the era of laterite weathering on nearby land) correlates with the periods of Cenomanian–Turonian events (OAEs, Bonarelli event; C/T OAE, OAE2, ~93 Ma).

Five sedimentation regimes can be distinguished, which are reflected in the mineral composition of rock cement.

(1) Coastal–marine conditions have been noted in all formations (chlorite–mica assemblage).

(2) Epicontinental conditions have been noted in Triassic coal deposits (Ostrovorusskaya and Bogatinskaya groups), in the Lipovetskaya and Kemskaya? formations (presence of kaolinite) (Lower Creta-

ceous), and in the Suchanskaya Group (kaolinite–mica assemblage under coal accumulation conditions).

(3) The Lipovetskaya and Galenkovskaya formations and the Suchanskaya, Korkinskaya, and Primorskaya groups (corrensite–chlorite assemblage) are characterized by coastal–marine conditions with possible evaporation of seawater.

(4) Coastal–marine conditions with possible evaporation of seawater and increased supply of calcium to sedimentary basins were noted for the Galenkovskaya Formation ("Galenkovskoe" time) and Suchanskaya and Korkinskaya (Frentsevskaya Formation) groups (corrensite–chlorite–laumontite assemblage).

(5) Epicontinental deposits under chemical weathering conditions in a humid subtropical climate have been noted in the upper part of the Korkinskaya Group (redbeds, rectorite assemblage, Romanovskaya Formation).

The latest data (Golovneva et al., 2021) for southern Primorye give two absolute ages for the Early Cretaceous period of coal accumulation: 118 ± 1.4 and 109 ± 1.0 Ma for the Lipovetskaya (Nikanskaya Group) and Frentsevskaya (Suchanskaya Group) formations, respectively. They are close to the sedimentation periods and conditions identified by the author of this work. It is possible to clarify the time of existence of the kaolinite–mica assemblage (the period of coal accumulation or the first Lipovetskian event)—older (ancient) 118 ± 1.4 Ma, and found in other formations of Primorye (Kemskaya?, Lower Cretaceous). The presence of chlorite–corrensite and chlorite–corrensite–laumontite assemblages, which can appear in two stages, can be correlated with several periods: (1) chlorite–corrensite assemblage, younger than 118 Ma, second Lipovetskian event (113–115 Ma) and (2) chlorite–corrensite–laumontite around 109 ± 1.0 Ma, the Galenkovskian (event) (probable an analogue of the Frentsevskaya Formation of the Suchanskaya Group, Lower Cretaceous).

Since the data for Primorsky krai are more detailed, it is possible, in the author's opinion, to extend the results to less studied areas. It is noteworthy that some Lower Cretaceous rocks of the Yamato Rise (Sea of Japan) may also have similar formation stages, since similar mineral assemblages were found there (Mozherovsky and Terekhov, 1991, 1998, 1999, 2016). Some rock samples from the North Yamato Ridge are probably about 118 ± 1.4 Ma (kaolinite–mica assemblage) and possibly slightly younger (113–115 Ma, presence of corrensite, corrensite-like? varieties and laumontite). The presence of epsomite, barite, ankerite, analcime, and signs of brine evolution in silty mudstones indicate that the conditions for seawater evaporation in the Early Cretaceous near the Yamato Rise were more pronounced than in coastal sedimentary basins. Perhaps, in the Late Cretaceous, the vicinity of the Yamato Rise could have been a provenance area of sedimentary material to areas of Southern Primorye for deposits similar to the upper parts of the Korkinskaya Group (redbeds of the Romanovskaya Formation of Cenomanian age?). Some samples recovered on the Yamato Rise are represented by confluent (massive) goethite, which could have formed during laterite weathering. In truth, similar samples have not yet been found in Southern Primorye.

Samples from the Upper Cretaceous rocks of Primorye (Primorskaya Group) are much less well characterized. There is the predominant mica–chlorite assemblage, an increase in the proportion of mixed-layer types of chlorite–smectite (corrensite-like) and mica–smectite (rectorite-like), mica, defective chlorite, a decrease in the corrensite content, and the absence of kaolinite. All other studied areas with Upper Cretaceous deposits (Terpeniya Peninsula, Shikotan Island, underwater Vityaz Ridge, Western and Eastern Kamchatka) are with rare exceptions mineralogically similar to the above-described Primorye sediments. On the Terpeniya Peninsula (Uchirskaya Formation, Maastrichtian–Danian, Kotikovskaya Group) and on Shikotan Island (Krabozavodskaya, Matakotanskaya, and Malokuril'skaya formations), analcime and stilbite appear in rock cement. Corrensites in Cretaceous rocks were recorded in the time intervals 113–120, 110–113, 105–110, 93–95, and 72–83 Ma.

Cenozoic deposits of Primorye, the Primorsky underwater slope, the Yamato Rise, the Sakhalin and Shikotan islands, the Vityaz Ridge, and the Kamchatka Peninsula have been partially characterized mineralogically in (Chudaev, 1977, 1978; Markevich, 1985; Mozherovsky and Terekhov, 1998, 2016; Vashchenkova et al., 2009, 2011; Mozherovsky, 2016, 2019, 2021). The main pattern is the initial corrensitization and rectoritization in the Miocene–Oligocene and the presence of corrensite in Paleocene–Oligocene rocks of Primorye, the Paleocene deposits of Sakhalin and Shikotan islands, the underwater Vityaz Ridge, in the absence of the corrensite–chlorite assemblage, and the presence of laumontite in Oligocene–Miocene rocks of Southern Primorye, while its proportion in other areas is decreased. The presence of corrensite with laumontite has been noted in Paleogene rocks of Eastern Kamchatka (Chudaev, 1977, 1978). The content of such zeolites as stilbite and chabazite in Paleocene–Oligocene deposits is slightly elevated. In Cenozoic sediments of the entire Far Eastern region, corrensites were found in the time intervals of 61–72, 56–61, 33–56 Ma, and the presence of laumontite was noted in the interval of 33–56 Ma (Mozherovsky, 2016, 2019, 2021).

Sedimentation conditions in the Cenozoic were probably the same: shallow-water, with a fairly warm climate, which contributed to mineral accumulation with subsequent alteration into corrensite. According to (Levitan et al., 2015), in the Cretaceous, as well as the Paleocene–Eocene, there were up to eight temperature maxima, during which salt-bearing deposits could have formed under seawater evaporation conditions.

Based on a study of authigenic and secondary mineral formation in Phanerozoic volcanosedimentary deposits, it can be concluded that new (more complete) data on Primorsky krai, the Sea of Japan, the Sea of Okhotsk, adjacent territories, the Lesser Kuril Arc, and the underwater Vityaz Ridge make it possible on a mineralogical level to establish a direct relationship between them:

(1) The strongest alteration in the studied Phanerozoic deposits did not extend beyond the laumontite facies;

(2) During the epigenesis of sedimentary sequences, two parallel processes are observed (Kossovskaya and Drits, 1971): the progressive alteration of smectite into mica in oxidative (an oxygen-saturated environment) conditions in the presence of potassium and chloritization under the condition of excess calcium and magnesium in reducing (oxygen-deficient) conditions. Thus, the alteration of smectite into mica reflects the course of epigenetic processes, and into corrensite, specific sedimentation conditions for a given region. Corrensite-like minerals may have a dual genesis and could have formed both in the process of epigenesis during alteration of smectite, and as a result of alteration of magnesium silicates, such as sepiolite or palygorskite (Millo, 1968; Hauff, 1981). It should be noted that from south to north, the magnesium content of corrensite increases (Mozherovsky, 2021, 2022), which may indicate a meridional direction of the salinization.

Analysis of the presented data on authigenic minerals combined with available general geological information makes it possible to clarify the nature of post-sedimentary rock alterations and conditions and geodynamic settings of sediment formation, and, as a result, supplement existing ideas about the history of geological development of the entire Far Eastern region. However, it must be added that mineralogical analysis for these purposes is limited by the peculiarities of epigenetic processes occurring in sedimentary rocks and therefore imposes a number of restrictions. Epigenetic processes begin to manifest themselves mineralogically in Oligocene–Lower Miocene deposits (Vashchenkova, 1987; Vashchenkova et al., 2009, 2011; Mozherovsky, 2016, 2019, 2021). Smectite, the main authigenic mineral, becomes structurally ordered as sediments age (Kossovskaya and Drits, 1971), is reordered, which is manifested as an increase of intensity and decrease in the width of the 001 reflection, and amorphous silica begins alteration into low-temperature opal-C/T (Svininnikov, 1989). Only from the Eocene to the Early Cretaceous do highly ordered mixed-layer formations begin to dominate, and with age, only mica and chlorite remain.

Consequently, it is possible to most reliably, mineralogically characterize the rock formation conditions from the Lower Cretaceous to the Paleogene.

When studying authigenic mineral formation in Phanerozoic deposits, the following patterns are distinguished.

(1) Smectite is common in all sediments, from Oligocene to modern. Moreover, with aging of sediments and sedimentary rocks, the degree of its crystalline perfection increases. Occasionally it is found in more ancient deposits, which is most likely due to their weathering (degradation).

(2) Mixed-layer formations of the smectite–mica type (low-ordered) are also observed from the Oligocene to modern, sometimes in Upper Cretaceous deposits. Rectorite-like (highly ordered structures) appear at the turn of the Paleogene, as do corrensite-like structures. The rectorite is most precisely associated with the tops (redbeds) of the Korkinskaya Group (Lower–Upper Cretaceous, Southern Primorye). In the sediments of Primorye, corrensite in assemblage with laumontite appears in the Early Cretaceous and again in the Oligocene (Romashka village, area of the Slavianka district). In Paleogene rocks, corrensite (without chlorite) has been noted near the village of Posyet, on the Yamato Rise (Sea of Japan), the Terpeniya Peninsula (Sakhalin Island, the Turovskaya and Ol'donskaya formations), and the Vityaz Ridge (Paleocene).

(3) Cristobalite has been recorded from a depth of 300–400 m in sediments of the Sea of Japan (Pliocene) to 1500 m in the Sea of Okhotsk (Paleocene), but is sometimes found in Maastrichtian–Danian rocks of the Uchirskaya Formation, Terpeniya Peninsula, Sakhalin Island (Vashchenkova, 1987; Mozherovsky et al., 2001; Svininnikov, 2004; Terekhov et al., 2010; Tsoy et al., 2005).

(4) Kaolinite (characterized by X-ray diffraction analysis) is found only in Triassic and Lower Cretaceous rocks of Primorye associated with coal-bearing deposits, as well as on the Yamato Rise (Sea of Japan).

(5) The sulfate group is present only in the Lower Cretaceous (epsomite, chermigite, thenardite, barite, gypsum) and Paleocene (barite, gypsum) sediments of the Yamato Rise (Sea of Japan) (Mozherovsky and Terekhov, 1991, 1999; Mozherovsky and Terekhov, 1998, 2016; Terekhov et al., 2013; Terekhov et al., 2016). Quite often, barite is also found in younger sediments in the form of nodules (Derkachev et al., 2000, 2015).

(6) Zeolites such as laumontite and analcime are found in Lower Cretaceous and Paleocene rocks of Southern Primorye, the Yamato Rise, the Terpeniya Peninsula (Sakhalin Island) (Mozherovsky and Terekhov, 1999, 2016; Mozherovsky, 2019, 2021a, 2021b, 2022), and Eastern Kamchatka (Chudaev, 1977, 1978). Heulandite and stilbite are found mainly in volcanosedimentary and sedimentary rocks from the

Cretaceous to the Miocene, and phillipsite is found in altered basaltoids from the Oligocene to the Pleistocene (Mozherovsky, 1986, 1995).

(7) Calcite is very widespread from the Permian to the Pleistocene and occurs in the form of nodules, ooids, veins and streaks, rarely in the form of layers 5–10 cm thick (Turovskaya Formation, Terpeniya Peninsula) (Mozherovsky, 2016; Mozherovsky and Terekhov, 2016).

(8) In all studied sedimentary basins, the presence of mixed-layer minerals of the chlorite–saponite type (corrensite-like) in Lower Cretaceous and Paleogene rocks has been noted. Moreover, their presence is unrelated to the type of volcanosedimentary material. In most sediments, the source of sedimentary material was acid and medium continental crustal rocks: Southern Primorye, the Yamato Rise (Sea of Japan) (Floor Geology..., 1987; Kutub-Zade et al., 2013) and the underwater Vityaz Ridge (Kuril–Kamchatka Trench) (Lelikov et al., 2008; Terekhov et al., 2012). An exception is volcanosedimentary rocks of the Uchirskaya Formation (Maastrichtian–Danian) of the Terpeniya Peninsula (Sakhalin Island) (Tsoy et al., 2005; Terekhov et al., 2010), partially the Malokuril'skaya (Maastrichtian–Danian) and Zelenovskaya (Paleocene–Miocene, Shikotan Island) formations (Palechek et al., 2008; Markevich et al., 2012; Terekhov et al., 2012) and the Kronotsky Peninsula (Chudaev, 1977, 1978) with a significant proportion of igneous rock material.

(9) The presence of two parallel trends in the mineral alteration of smectite, noted by other researchers (Kossovskaya and Drits, 1971), has been confirmed: into mixed-layer formations of the mica–smectite type (rectorite-like) and smectite–chlorite (corrensite-like).

(10) The distribution of authigenic minerals exhibits latitudinal and depth–age zoning. Southern and northern zones are distinguished: the first is characterized by the presence of kaolinite (Triassic, Early Cretaceous of Primorye) and sulfate group minerals in the Lower Cretaceous rocks of the Yamato Rise, and the second is the absence of kaolinite.

The corrensite–laumontite assemblage requires a more detailed discussion. The first identification of the zeolite subsidence facies and description of its zoning was made by D. Coombs (1960) for the thick volcanogenic Triassic greywacke complex of New Zealand. A similar pattern appears in other regions of the Earth: in green tuff formations, as well as in Neogene–Paleogene and Mesozoic formations of Japan (Iijima and Utada, 1971; Kimbara and Sudo, 1973), Iceland (Walker, 1960; Mehegan et al., 1982), and Kamchatka (Naboko and Berkhin, 1970; Chudaev, 1977, 1978; Markevich, 1985).

Ferromagnesian corrensites often occur in humid coal-bearing formations. They were studied in most detail in the Cretaceous coal-bearing formation of Western Verkhoyansk (Kossovskaya et al., 1960; Kossovskaya, 1961; Kossovskaya and Drits, 1985). Kossovskaya and Shutov (1971) first established the assemblage of this type of corrensites with the laumontite zone of zeolite facies of regional epigenesis and proposed a unified mechanism of its formation for the Cretaceous and Paleogene–Neogene volcanic-clastogenic complexes of the Pacific belt and other regions of the Earth. It was noted that the appearance of the laumontite zone is due to regional epigenesis processes and correlates with the refractive index of vitrinite and release of volatiles (Kisch, 1975; *Low Temperature*..., 1987). It is confined to the interval between long-flame and steam-fat coals (coalification temperature 70–200°C). The recurrence of the corrensite–laumontite assemblage is especially noted in the Triassic, Lower Cretaceous and Eocene of the Vilyui syneclise (Kossovskaya et al., 1960; Drits and Kossovskaya, 1990, 1991), the Triassic of New Zealand (Coombs, 1960), the Upper Cretaceous and Paleogene of the Kamchatka Peninsula (Chudaev, 1977, 1978; Markevich, 1985; Koporulin, 1992, 2006), Maastrichtian–Danian, and Paleocene–Eocene of Sakhalin Island (Koporulin, 1992; Mozherovsky, 2022), the Tertiary and Quaternary volcanosedimentary complexes of Sumatra (Hall and Moss, 1997), and for zeolites of the clinoptilolite–heulandite group, they are confined to Upper Cretaceous and Paleogene deposits (Kossovskaya et al., 1980). Similar zoning has been noted for Cretaceous–Paleogene deposits of the northern Asian continent–Pacific Ocean transition zone (Mozherovsky and Terekhov, 2016; Mozherovsky, 2022).

The author of this study suggested that the formation of the corrensite–laumontite assemblage is associated with two coinciding global climatic events: the creation of conditions favorable for evaporation of seawater and anomalously high supplies of calcium to sedimentary basins (Mozherovsky, 2022).

Another peculiarity of the Vilyui syneclise is the presence of corrensite in Triassic sediments (Drits and Kossovskaya, 1990, 1991). In Primorye, corrensite was discovered in Upper Triassic rocks (Mozherovsky, 2021). The author suggested that a possible reason for its discovery is inaccurate determination of the age of rocks and proposed transferring part of these deposits to the Lower Cretaceous. At the same time, another version is possible: the presence of corrensite precisely in Triassic rocks of Primorye further emphasizes the mineralogical proximity of these sedimentary basins, although they are located in different climatic (vegetation) zones (Vakhrameev, 1988; Markevich, 1995).

CONCLUSIONS

Study of authigenic mineral formation in Cretaceous–Cenozoic volcanosedimentary complexes of the Sea of Japan, Sea of Okhotsk, underwater Vityaz Ridge, and the islands of Shikotan and Sakhalin (Terpeniya Peninsula) has made it possible to refine the paths of epigenetic alterations, sedimentation conditions, and paleogeographic formation conditions in sedimentary basins of the Russian Far East. Information on mineral assemblages, chemical composition, geochemistry of elements, systematic composition of palynocomplexes (Mozherovsky et al., 1983, 1989, 2001; Mozherovsky, 1986, 1995, 2016, 2019, 2021a, 2021b, 2022; Gnidash et al., 1988; Mozherovsky and Terekhov, 1991, 1998, 1999, 2016; Tsoy et al., 2005; Palechek et al., 2008; Terekhov et al., 2008, 2010, 2011, 2012; Markov et al., 2009; Vashchenkova et al., 2009, 2011; Markevich et al., 2012) makes it possible to hew to the conclusion of (Kossovskaya and Shutov, 1971) that they formed under conditions of interaction of two parallel processes: chloritization with excess magnesium and hydromica with excess potassium.

Sedimentation near the Yamato Rise in the Early Cretaceous and Paleocene occurred in a shallow-marine salinizing basin with slow sea transgression and a hot arid climate. To the north (Sakhalin and Kuril islands) the climate was somewhat colder, but sedimentation conditions still contributed to the formation of high-magnesian silicates. Two mineral assemblages have been established, reflecting different conditions during the formation of sedimentary strata: the first assemblage—corrensite, analcime, epsomite, ankerite, and calcite—is characteristic of salt-bearing basins; the second—kaolinite, mica, mica—smectite mixed-layer formations—reflects the sediment alteration conditions during epigenesis.

The similar composition of minerals in Lower Cretaceous and Paleocene rocks of the Yamato Rise indicates the cyclicity of mineral formation for the Early Cretaceous—Paleogene period. Perhaps when studying older sedimentary rocks in other sedimentary basins, this cyclicity will be discovered.

Epigenetic alterations of Cenozoic volcanic and sedimentary rocks of the Far Eastern region were also expressed in two parallel processes: smectitization with sufficient potassium content in conditions of excess oxygen, and new formation of opal-C/T, which took place under conditions of intense subsidence of the sedimentary basin, starting from the Early Miocene.

A mineral series is also noted for zeolites, starting with laumontite in Lower Cretaceous and Paleocene sedimentary rocks through a series of zeolites of the stilbite and analcime group and ending with phillipsite in Cenozoic volcanic rocks.

In surface and near-surface conditions, smectite occupies a subordinate position, where the dominant detrital minerals are chlorite and mica, which characterize the provenance areas.

In Neogene volcanosedimentary deposits, smectite becomes the predominant mineral, associated with mixed-layer formations of the smectite—mica type and cristobalite. Probably, this should also include formations that form a continuous series from nontronite to celadonite in association with quartz, as well as the initial celadonitization of basalts.

For Upper Cretaceous volcanosedimentary rocks, highly ordered mixed-layer (corrensite-like and rectorite-like) minerals become dominant, associated with defective chlorite and laumontite. The older formations are dominated by mica and chlorite. The alteration paths are also noticeably separated depending on the sedimentation conditions: mica and mica—smectite mixed-layer formations were probably formed during epigenesis from montmorillonite through a group of mixed-layer formations of the smectite—mica type (Kossovskaya and Drits, 1971). Corrensite-like minerals could have formed either as a result of the alteration of smectite with excess magnesium, or alteration of magnesian silicates such as sepiolite or palygorskite (Millo, 1968; Hauff, 1981). The source of sedimentary material was continental crustal rocks with a constant proportion of volcanic material (occasionally significant is the Zelenovskaya Formation of Shikotan Island). The thickness of accumulated sediments was approximately the same.

Lower and Upper Cretaceous rocks of the region are characterized by mica, chlorite, corrensite, mixed-layer mica—smectite type, kaolinite, defective chlorite, analcime, laumontite, stilbite, chabazite, quartz index minerals of the analcime facies of epigenesis and, possibly, laumontite; i.e., the strongest alterations did not extend beyond the laumontite facies. The probable subsidence depth of rocks of this age, based on mineralogical data, is estimated as 2—5 km (Aoyagy and Kazama, 1980; Karnyushina, 1987).

Generalizing the research, the following conclusions can be drawn.

(1) Mesozoic—Cenozoic volcanosedimentary complexes in the northern Asian continent—Pacific Ocean transition zone formed synchronously and have a transgressive cycle. It began in the Upper Cretaceous—Paleocene with terrigenous basal conglomerates that formed in tectonically quiescent shallow-marine environments. Moreover, the source was acidic and medium rocks, characteristic of continental crust. This was followed by a stage of tectonic and volcanic activation. The proportion of volcanic material and depth of the basin increased. In the Oligocene—Miocene, sedimentation began to acquire siliceous specialization, then in the Pliocene—Pleistocene, the basin deepened, and sedimentation assumed modern features. The thickness of sediments in the studied basins could have exceeded 2—3 km.

(2) Diagenetic and epigenetic alterations of authigenic minerals in all studied basins have similar features and indicate the same conditions for the formation of Cretaceous—Paleogene rocks at the base of the volcanosedimentary sequence with a thickness of about 2—3 km and sialic provenance areas, which agrees with data from other research methods. In shal-

low–coastal conditions, minerals are formed, which, as a result of further alteration, turn into corrensite and rectorite, which probably depends on the salinity of the water in the sedimentary basin and depth. Corrensite forms in sediments that formed under conditions close to salt-bearing. Moreover, it predominates in sandstones, i.e., in shallow–coastal formations of lagoons and bays at moderately warm temperatures. Siltstones and silty mudstones (fine-grained rocks deposited in deeper water conditions and probably at lower temperatures) are characterized by corrensite-like and rectorite-like formations.

Cristobalite at this stage (Cretaceous–Paleogene) transforms into quartz. With the appearance of siliceous sediments in Oligocene–Lower Miocene deposits and their epigenesis, opal is transformed into cristobalite (Svininnikov, 2004). The proportion of detrital components—mica, quartz, plagioclase—decreases, and smectite and mixed-layer formations of the mica–smectite type begin to appear, then smectite-mica and an amorphous phase (probably opal), because diatoms begin to dissolve. Lastly, mineral formation acquires modern features, where the authigenic mineral in sediments is smectite, and the proportion of terrigenous components—mica, quartz and plagioclase—increases.

(3) In the studied basins, the minerals with the most striking indicative properties are corrensite, laumontite, cristobalite, and epsomite. Findings of corrensite and laumontite in sedimentary rocks may indicate that the estimated age of these rocks is no younger than the Paleocene–Eocene and the estimated thickness of sediments is at least 2–3 km; a relationship with salt-bearing deposits is possible. It should be suggested that similar deposits are present in other sedimentary basins of the Far East.

Cristobalite-bearing rocks are fractured and contain almost no clay minerals. Their outcrops on the surface of the basin bottom indicate large (at least 400 m) vertical movements of the crust (Mozherovsky et al., 2001; Vashchenkova et al., 2009).

The author hopes that the revealed patterns in authigenic mineral formation of the studied areas will foster similar studies in other sedimentary basins of Siberia and the Russian Far East.

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CONFLICT OF INTEREST

The author of this work declares that he has no conflicts of interest.

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