Geodynamic Setting on the Paleo-Asia Continent Eastern Margin in the Paleocene

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Abstract. The isotopic-geochemical and geochronological data obtained allow us to justify the middle Paleocene - early Eocene stage of magmatism within the Sikhote-Alin. The volcano-plutonic complexes of this stage are characterized by distinctive mineralogical and geochemical features of the А-type igneous rocks that differ greatly from the Late Cretaceous I-type igneous rocks, which imply a geodynamic regime other than subduction at the paleo-Asian eastern margin during this period. According to the geological-structural data of the Cretaceous and Paleogene parts of the Shimanto accretionary complex, this magmatic stage coincides with changing of the geodynamic mode of subduction of an oceanic plate by geodynamic mode of transform sliding of the latter along the paleo-Asian continent eastern margin and, again, by geodynamic mode of subduction of an oceanic plate.

1. Introduction

In recent years the Pacific margin of Asia attracts close attention of researchers as a potential source of various geological information for the development of models of the geodynamic evolution of the paleo-Asian continental margin in the Mesozoic-Cenozoic, and for clarifying the reasons for change in the kinematics of the relative motion of the Pacific plate, for example, in the Paleocene. However, the majority of researchers in their paleogeodynamic models proposed for such a large territory use materials on restricted regions of East Asia, such as Japan, Korea or northeastern China without mutual comparison and analysis of all data. Therewith, materials on the Sikhote-Alin region (south-east of Russia), that together with the abovementioned territories constituted a single eastern margin of the paleo-Asian continent in the Paleocene [e.g., 1 and references therein], are almost not used. This is due to both objective and subjective reasons. For example, as for igneous rocks this is mostly related with the bad coverage of the material, as the isotopic-geochemical and age data for this region are rather limited and fragmented, which often leads to distorted conclusions on the specifics of manifestations of the magmatic activity and evolution of convergent plate boundaries of the Western Pacific during the Late Cretaceous-Cenozoic. At the same time, the use of incomplete and not fully reliable data on the adjacent territories led to the development of misconceptions of the so-called magmatic gaps, i.e. the limited duration of magmatism at different periods of the early Paleogene throughout the entire eastern margin of the paleo-Asian continent. [e.g., 2 and references therein]. Such conclusions are based mainly
on the materials from the Japanese archipelago but expanded to the entire paleo-Asian continental margin and are explained by the global geodynamic reconstructions along its edge. However, it is difficult to imagine that the consequences of this reorganization could have arisen only within a separate area of the continental margin. On the contrary, the products of the Paleocene magmatism, that are synchronous with the suggested magmatic gap in Japan, are widely distributed within the Sikhote-Alin and have mineralogical and geochemical features inherent of A-type igneous rocks [e.g., 3 and references therein]. These features are typical for the mantle and crustal magmatism of extension zones, and they cannot be realized in the setting of orthogonal or oblique subduction that determines the compressional conditions at a convergent margin.

At the same time, the wrong interpretation of the periodicity and duration of the magmatic activity results in further incorrect conclusions on the specifics and succession of geological events. In particular, the suggested misconceptions about magmatic gap at the eastern margin of the paleo-Asian continent in the Paleocene was used by some researchers to reanimate the idea of subduction of the spreading ridge that separated the Pacific and Izanagi oceanic plates [e.g., 4, 5, etc.]. In this paper we substantiate the fallacy of allocation of the Paleocene magmatic gap and, respectively, geodynamic stage of the spreading ridge subduction in the Late Cretaceous-Paleocene based on the analysis of the available geological materials on different regions of East Asia. To fill in the missing data on the middle Paleocene to early Eocene (60.5–53 Ma) magmatic activity within the Sikhote-Alin the authors provide their own original and published data as well as other published data.

2. A brief history of the spreading ridge subduction argumentation

The idea of subduction of the spreading ridge separating the Izanagi (Kula) and Pacific oceanic plates is being used in the reconstructions of the Cretaceous-Paleogene geodynamic history of the Pacific margin of Asia for more than 30 years. Therewith, the time of the ridge subduction and related geological-tectonic events differs substantially in different publications. In the early publications it was assumed that the subduction of the spreading ridge of the Izanagi-Pacific plates that supposedly occurred at 90–80 Ma involved both the voluminous acidic (rhyolite) volcanism at the East Asia margin and the opening of the back-arc basin of the Sea of Japan [e.g., 6].

Another group of researchers [7, 8, etc.] determines the subduction time of the Isanagi-Pacific Ridge in the range of 60–55 Ma and associates the global Eocene reorganization of not only Pacific oceanic plates (e.g. bend of the axis orientation of Hawaiian Ridge-Emperor Seamount Chain), but also of the Southern Indian Ocean plates with this process (e.g. spreading cessation in the Tasman Sea and change in the Australian plate’s drift direction from northwestern to northern). They made these conclusions through the modelling of a set of oceanic paleoage grids (linear magnetic anomalies) from 140 Ma to the present using the spreading symmetry principle and data on the preserved, but multiple times fragmented isochrones of magnetic anomalies, and the interpretation of the modern structure of the mantle beneath the eastern margin of Asia based on the seismotomographic data.

In the Raimbourg and coauthors’ [9] work, the timing of the Izanagi-Pacific ridge subduction is suggested to be in the range of 48–43 Ma, which is almost 40 Ma later than it was assumed initially. This conclusion is based on the analysis, comparison and manifestation sequence of ductile and brittle deformations in the Cretaceous and Paleogene parts of the Shimanto accretionary belt on the Kyushu Island. At that, the presence of brittle and brittle-ductile deformations in both Cretaceous and Paleogene accretionary complexes in the form of multiple thrusts and asymmetric to isoclinal folding is connected to the subduction of the oceanic plate, while the presence of metamorphic foliation in terrigenous rocks in the basement of the Cretaceous part of the accretionary complex limited by the zone of the large Nobeoka thrust that separates the Cretaceous part from the Cenozoic part of the Shimanto belt, is attributed to the spreading ridge subduction.

Recently proposed versions of the Izanagi-Pacific ridge subduction [4, 5] are mainly based on the idea of a stratigraphic (age) gap in the accretionary complexes of the Shimanto belt, magmatic gap and structural unconformity in the early Cenozoic forearc basin sediments in the Paleocene–early Eocene (~58–46 Ma). The Shimanto belt of the south-western Japan is a classical example of an ancient
accretionary prism formed, as it is thought, during the continuous Late Cretaceous-Miocene subduction of an oceanic crust [e.g., 2, 10, etc.]. It consists of repeatedly alternating tectono-stratigraphic slices composed of coherent and melanged fragments of the sedimentary cover and basaltic layer of the oceanic crust and separated by low-angle thrusts. Based on the microfauna data (radiolarians, foraminifera) the Shimanto terrane is divided into two subterranes: Cretaceous and Cenozoic. A large thrust called the Nobeoka tectonic line on Kyushu Island, or Aki tectonic line on the Shikoku Island, or Gobo-Hagi tectonic line on the Kii peninsula of the Honshu Island is assumed to be the boundary between them. Traditional opinion based on the early paleontological dating is that the youngest age for the Cretaceous part of the Shimanto belt is considered Maastrichtian, and the oldest age for the Cenozoic part is the early Eocene, which is at the heart of the view that there is a stratigraphic (age) gap in the formation of this accretion complex. At the same time, a sufficient number of publications indicate the Paleocene age of a part of the structurally lowermost tectono-stratigraphic units of the Cretaceous Shimanto accretionary formations. For example, on the Shikoku Island the lowermost structural level of the Cretaceous Shimanto (Magi complex), according to the results of U-Pb dating of detrital zircons, show that the mélange and coherent formations of the Magi complex are of early-middle Paleocene age. The youngest cluster of zircons from the mélange matrix are 62.7±1.7, and from the sandstones of the lower part of the complex - 62.0±1.3 Ma [11]. Similar age data for the Magi complex were obtained at the eastern coast of the Shikoku Island [12], where it is represented by a set of sixfold repeated tectonic slices made up of foliated black siltstones and horizons of chaotic formations (mélange containing blocks and fragments of siliceous mudstones, cherts, basalts, sandstones), and interbeds of felsic tuffs. The results of U-Pb dating of the zircons from the tuff interbeds indicate 66.2±3.5 – 76.2±2.4 Ma for the upper slices and 57.9±2.9 – 63.5±3.8 Ma for the lower slices. These data conform with the paleontological (Radiolarians) determinations showing the Paleocene age of the lower structural units of the Magi complex [13]. Hence, the data provided above demonstrate the absence of any significant age gap in the terrigenous rocks of the Shimanto complex, though the cut-sections of continuous Late Cretaceous-Paleocene sequences are rare due to the imbricate-thrusted structure of the Shimanto belt.

The analysis of the available data on igneous rocks also does not confirm the supposition that there was a magmatic gap in the early Paleogene. Despite the existing opinion of the significant decrease of the supra-subduction magmatism in the early Paleocene of Japan [e.g., 14, etc.], the Paleocene volcano-plutonic rocks are rather widely distributed in the north-western part of the Inner Zone of Japan, in the south-eastern part of China and Korean peninsula, and in the Sikhote-Alin

3. Paleocene magmatism of the Sikhote-Alin

According to the geological mapping, the Paleocene felsic rocks are widely distributed within the Sikhote-Alin, but the precision isotopic-geochemical and age data cited in the literature are quite limited and miscellaneous, which often leads to nonobjective conclusions on the character of the magmatic activity or even existence of a magmatic gap during this period [e.g., 14]. These Paleocene rocks are represented by rhyodacite-rhyolitic and leucogranite complexes. The rhyodacite-rhyolitic complex combines the volcanic, extrusive and vent rocks of acidic or moderately acidic composition that formed multiple volcanic depressions and calderas of subsidence. The size of some of them, taking into account the erosion reaching the shallow magmatic chambers, is 40x20 km [15], while the total volume of the Paleocene volcanic products greatly surpasses that of the Yellowstone caldera.

The facies diversity of pyroclastic rocks consists in various stages of the explosive process of the ignimbrite formation. The rhyodacite-rhyolitic ignimbrites and voluminous bodies of the volcanic glasses contain large quantities of quartz, albite-oligoclase, ferrohyperstene, ferrohedenbergite, sanidine, ferrosaugite, biotite, and fayalite. Dominating accessory minerals are orthite, ilmenite, zircon, apatite, native iron and cohenite (Fe,C), which suggests a highly reduced composition of the primary melts [15]. The granitoids are genetically related to the Paleocene acid volcanic rocks, which explains why these intrusions are spatially limited to the volcanic fields of the East Sikhote-Alin area. The sheet-like granitoid bodies intrude between volcanic strata, sealing off volcanic conduits and dikes, and fill ring and radial faults within volcanic depressions. Almost all of these intrusions are associated with
subvolcanic endocontact zones that contain highly porphyritic rocks with poorly crystallized felsic, spherulitic, or auloclastic texture. The rocks are primarily alkali-feldspar-granites and leucogranites, rarer aegirine–riebeckite granites, and quartz-syenites. The former two types have phenocrysts that consist predominantly of oligoclase (up to 40% modal abundance), quartz, perthitic alkal feldspar, and hypersthenes, and more rarely of magnetite, augite, hornblende, and biotite. The aegirine–riebeckite granites are fine-grained, porphyritic, or pegmatitic rocks that contain variable proportions of quartz, alkali feldspar, albite, aegirine, and riebeckite. Accessory minerals are zircon, xenotime, and bastnaesite, and more rarely columbite, chevkinite or orthite [15, 16 etc.].

To establish the precise age limits of the manifestation of the Paleocene volcanism within the South Sikhote-Alin we performed U–Pb zircon SHRIMP dating of samples from rhyodacite-rhyolitic volcanic complex. The obtained results together with the others published data indicate that in the Sikhote-Alin magmatism occurred predominantly at ~ 60–53 Ma, i.e. in the Paleocene.

The geochemical data of the Paleocene rocks show that they have SiO₂ concentrations of typically 65–75 wt.%, and up to 82 wt.%. They are characterized by high alkali concentrations (K₂O+Na₂O or 6.8–10.5 wt.%) and extremely low CaO and MgO concentrations, which is reflected in their high to middle potassium, high-alumina, alkalic and ferruginous compositions. Wide variations of concentrations of LIL elements (K, Rb, Cs, Sr и Ba), higher concentrations of HFSE (Zr, Nb, Ga и Y) and REE (except Eu) are also typical of them. The calculated T₂ and T₃ are predominantly more than 800°C allowing to suggest that the primary melts were of high-temperature. In the multicomponent diagrams the chondrite normalized compositions of the rocks are similar to the rare-earth spectra, showing an insignificant enrichment with LREE/HREE (3.5–10.5) at low values of the (La/Yb)ᵣ ratios (0.9 и 2.2–10.6) and negative Eu anomaly. In the spider diagrams the primitive mantle-normalized trace element, the rocks show negative Ba, Sr, and Ti and positive K, Th, U, and Pb, and also partially positive Ce, Zr, and Hf anomalies, i.e. they demonstrate characteristics typical of geochemical A-type igneous rocks. Their position in the discriminant diagrams indicates the same [17, 18, 19].

4. Discussion and conclusion
The absence of wide distribution of the middle to late Paleocene (60.5–53 Ma) supra-subduction igneous rocks in the Sikhote-Alin and adjacent areas allows us to suggest that subduction along the paleo-Asian continent eastern margin ceased in the early Paleogene. This conclusion is additionally confirmed by the essentially tergenous composition of the Paleocene sedimentary formations characterized by almost total absence of pelagic and hemipelagic sediments. For example, on the Kii peninsula the Paleocene sedimentary rocks (Ononashigawa complex) are represented by the alternating packs of sandstones and siltstones that alternate with thick beds of coarse-grained sandstones and interbeds of conglomerates the total thickness of which is approximately 2000 m [e.g., 20, etc.]. On the Shikoku Island the structurally lowermost tectono-stratigraphic unit of the Magi complex, that contains the early Paleocene detrital zircons, is also composed of rhythmically alternating members of sandstones and siltstones [e.g., 21]. In case of the continuous subduction the cut-sections of these complexes should have included the fragments of the Ocean Plate Stratigraphy Sequences.

On the other hand, the wide occurrence of the Paleocene volcano-plutonic complexes of A-type prevents from interpreting the eastern margin of the paleo-Asian continent in the early Paleogene as a passive margin. Thereby, out of three alternative variants - passive margin, active subduction margin and active transform margin, only the last one remains possible. The differences in the structural ensembles of different-aged tectonic-stratigraphic complexes of the Shimanto belt, i.e. the spatial orientation of the deformation structures of the melanged and coherent formations of which they are composed, are additional evidence for this. Particularly, the Magi complex, the youngest (Maastrichtian) and structurally lowermost unit of the Cretaceous part of the Shimanto belt on the Shikoku Island that forms the base of the hanging wall of the Aki thrust, is made up of the normal layered and melanged terrigenous rocks crumpled into different-amplitude asymmetric folds of east-north-eastern strike (50–60°, in modern coordinates) [e.g., 22, etc.]. The results of the analysis of spatial geometry of the deformation elements in both cataclasized terrigenous rocks and mélanges show, according to the
abovementioned authors, that the rock deformation took place under the conditions of a parallel to the deposit bedding simple thrust caused by the low angle oblique subduction.

Unlike the Magi complex, within the Murotohanto complex [after 23] or Naharigawa complex [after 21], which is the oldest (Paleocene-Eocene) and structurally uppermost tectonic-stratigraphic unit of the Cenozoic part of the Shimanto belt laying directly under the Aki thrust, two stages of the deformation structures are distinguished. The first (early) stage, during which the sedimentary deposits were crumpled into different-amplitude asymmetric folds of latitudinal (WE) strike (in modern coordinates), is manifested only in the northernmost part of the complex containing Paleocene microfauna [23]. During the second (late) stage of deformations, the sedimentary deposits of the entire Murotohanto complex (both northern part and southern part, the age of latter of which on the basis of microfauna is determined as the early to middle Eocene) were crumpled into the asymmetric folds of NE strike. The difference in the orientation of the deformation elements of the rocks is approximately 30°, which indicates the counterclockwise rotation of the vector of relative motion of an oceanic plate in the early Eocene and the change in the convergence angle [23].

Taking into account the difference between the kinematic regimes of formation of the deformation structures of the youngest unit of the Cretaceous Shimanto, Paleocene and Eocene units of the Cenozoic Shimanto, and also the formation of the tectonic-stratigraphic slices of the Magi complex during oblique subduction, there are all reasons to state that in the Late Cretaceous-early Eocene the Pacific plate changed twice its motion direction with respect to the paleo-Asian margin, i.e. from the north-western (oblique subduction) in the Late Cretaceous to the submeridional (middle to late Paleocene) and back to the north-western (early Eocene). This conclusion does not contradict the data on the directions of relative motion of the Pacific oceanic plates in the considered time interval [24] determined on the basis of linear magnetic anomalies and fixed hot spots, and assumes the domination of the transform margin regime at the eastern edge of the paleo-Asian continent in the Paleocene. It should additionally be noted that the transform margin regime in the Paleocene-early Eocene (60–53 Ma) was also justified by the data of the structural-biostratigraphic research on the Cenozoic part of the Shimanto belt (Hyuga complex) on Kyushu Island [25].

Taking into account the abovementioned geological-structural data and the fact that the Paleocene volcanic formations in the Sikhote-Alin overlie with clearly defined structural unconformity the Late Cretaceous magmatic complexes, the youngest age of which according to the U–Pb (SHRIMP) dating of diorites is 60.45±0.65 Ma [26], the geodynamic mode of subduction along the eastern edge of the paleo-Asian continent was replaced by the geodynamic mode of oceanic plate transform sliding in the Middle Paleocene (~60.5 Ma). This is also confirmed by the precision geochronological data on zircons from the Sikhote-Alin igneous A-type rocks. But, already in the early Eocene (54 Ma) the subduction regime resumed, which is evidenced by the formation of the Eocene to Middle Miocene accretionary complexes, and by the manifestation of the synchronous supra-subduction magmatism, which are studied in detail in Jahan [e.g., 2, etc.].

This change in the geodynamic mode in East Asia can be described by a model of subparallel ridge-crest–trench collision that stalls subduction causing the break-off of the spreading ridge in the deep-sea trench, and the formation of large-scale strike-slip deformations of the continental margin as is the case with the California transform margin of the USA and Mexico [e.g., 27 etc.] but does not exclude ordinary transform sliding of an oceanic plate lacking any submarine rises or ridges. This, in turn, requires further and more detailed geological-structural and petrological-geochemical investigations.

5. References
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