The "puzzle" of the primary obsidian source in the region of Paektusan (China/DPR Korea)

Vladimir K. Popov [a, *], Yaroslav V. Kuzmin [b, c, *], Andrei V. Grebennikov [a, d, *], Michael D. Glascock [e], Jong-Chan Kim [f], Clive Oppenheimer [g], Sergei Y. Budnitskiy [a], Mi-Young Hong [h], Ju-Yong Kim [i]

[a] *Far Eastern Geological Institute, Far Eastern Branch of the Russian Academy of Sciences, Vladivostok 690022, Russia*

[b] *Sobolev Institute of Geology and Mineralogy, Siberian Branch of the Russian Academy of Sciences, Novosibirsk 630090, Russia*

[c] *Laboratory of Mesozoic and Cenozoic Continental Ecosystems, Tomsk State University, Tomsk 634050, Russia*

[d] *Far Eastern Federal University, Vladivostok 690950, Russia*

[e] *Research Reactor Center, University of Missouri, Columbia, MO 65211, USA*

[f] *School of Physics, College of Natural Science, Seoul National University, Seoul, 08826, Republic of Korea*

[g] *Department of Geography, University of Cambridge, Cambridge CB2 3EN, UK*

[h] *Gyeore Institute of Cultural Heritage, Gyeonggi-do, 10523, Republic of Korea*

[i] *Korean Institute of Geoscience and Mineral Resources (KIGAM), Daejeon, 34128, Republic of Korea*

Abstract

Since the 1990s, a characteristic obsidian geochemistry has linked widespread archaeological assemblages spanning the Russian Far East, Korean Peninsula, and Northeast China. Referred to as PNK1, the source of this material has yet to be identified. As a contribution to solving this enduring puzzle, we report here analyses of a commercial specimen of obsidian exported from Chongjin in DPR (North) Korea. A combination of Neutron Activation Analysis (NAA) and Potassium–Argon dating enable us to compare this piece with a large obsidian database for Northeast Asia. We find that the "Chongjin sample" is identical to PNK1 lithics from archaeological collections. While the exact source of the "Chongjin sample" remains unknown, we can more confidently locate the primary source for PNK1 lithics in DPR Korea. Based on an exhaustive literature review of the geology and geochemistry of volcanic glasses and other volcanic rocks in the northern part of the Korean Peninsula, and drawing on our own

unpublished data, we suggest that the PNK1 source is most likely located either south of Paektusan Volcano, or to its east in the Kilju–Myongchon region. This corroborates the existing evidence for the long-range transport of the material.

* Corresponding authors. Far Eastern Geological Institute, Far Eastern Branch of the Russian Academy of Sciences, Vladivostok 690022, Russia; and Sobolev Institute of Geology and Mineralogy, Siberian Branch of the Russian Academy of Sciences, Novosibirsk 630090, Russia. *E-mail addresses:* vladpov@fegi.ru (V.K. Popov), kuzmin@fulbrightmail.org (Y.V. Kuzmin), greandr@hotmail.com (A.V. Grebennikov)

Keywords: obsidian, geochemistry, Paektusan, DPRK (North Korea), geoarchaeology, Northeast Asia

1. Introduction

Geochemical fingerprinting of obsidian artifacts and source rocks (Cann and Renfrew, 1964; Shackley, 2005; Carter, 2014) has turned out to be one of the most effective and reliable means to understand patterns of prehistoric contact and migration (e.g., Williams-Thorpe,1995). The approach has been applied to many regions of the world but its most intensive application has been in the Mediterranean and Near East, and the Americas (Skinner and Tremaine, 1993; Pollmann, 1999). In Northeast Asia, obsidian studies focused initially on Japan, where sourcing of archaeological obsidian has been undertaken since the early 1970s (e.g., Suzuki, 1973; Ono, 1976). By the early 1990s, this attention spread to the neighboring regions of the Russian Far East, the Korean Peninsula, and Northeast China (Manchuria) (see summaries in Kuzmin, 2014, 2017).

Obsidian ("nonhydrated rhyolitic glasses … of quenched, liquid magmatic compositions"; see Macdonald et al., 1992: 1) is usually associated with silicic lavas such as rhyolites (e.g,. Cann, 1983). In Northeast Asia, such rocks are found mostly within the volcanic arcs of Japan (e.g., Wakita, 2013) and the Kamchatka Peninsula of Russia (e.g., Khain, 1994). However, three additional types of obsidian sources are recognized on mainland Northeast Asia. The first two are associated with Cenozoic basalts (the majority of cases) and rhyolites of the southern Russian Far East and have been well studied (e.g., Kuzmin and Popov, 2000; Glascock et al., 2011; Popov et al., 2009; Doelman et al., 2008, 2012). The location of the third source type is unknown but indications have pointed to the region of Paektusan Volcano, situated along the border between the People's Republic of China (PRC) and Democratic People's Republic of Korea (DPRK or North Korea) (Figure 1). Paektusan is an intraplate volcano constructed from trachytes, comendites and subalkaline rhyolites (e.g., Popov et al., 2005, 2008; Sakhno, 2007). Its geography and general geology were initially studied in the late nineteenth century, during the course of European exploration of China (James, 1888) and reconnaissance for the Chinese Eastern Railroad built by Russia (Anert, 1904; Garin-Michailowski, 2005 [1898]; see also Stephan, 1994: 58–61).

Since the mid-to-late 1990s, numerous obsidian artifacts from the Primorye Province of Russia, Korean Peninsula, and Manchuria (Kuzmin et al., 2002; Popov et al., 2005; Kim, 2014; Kim et al., 2007; Jia et al., 2010, 2013; Chang and Kim, 2018) were found to have the share a common geochemical signature, referred to as "Paektusan Volcano-1" (Kuzmin et al., 2002) and later as "PNK1" (Paektusan – North Korea Type 1) (Popov et al., 2005). This geochemical group was first identified from two obsidian flakes (see Kuzmin et al., 2002: 513) acquired from DPRK scholars by Soviet archaeologists in 1974, with the information that it came from the region of Paektusan (A.K. Konopatsky, pers. comm. 1992; see also Kuzmin and Popov, 2000). The search for the source material has thus far been hampered by the limited contacts between international scholars and geologists and archaeologists in DPRK. Several fieldwork campaigns over the past 15 years on the Chinese side of Paektusan have failed to reveal the specific source (Popov et al., 2005, 2008; Sakhno, 2007; Kim, 2014), and, hitherto, we have been unable to obtain additional 'geological' obsidian samples that match the PNK1 geochemistry.

Our aim here is to narrow the search for this enigmatic obsidian source. Resolving this question will be of considerable geoarchaeological significance because this obsidian was widely used in prehistory for tool-making over a large territory spanning the Primorye and Amur River regions of the Russian Far East, Korean Peninsula, and Manchuria (e.g, Kuzmin, 2017) (Figure 2).

2. General information about the Paektusan Volcano

2.1. Geography and geology of Paektusan

The name Paektusan is derived from the Korean "*Paek*" (white), "*tu*" (head), and "*san*" (mount). It is so-called in recognition of its appearance – snow-covered in winter, and, still light-coloured after the thaw exposes pale pumice deposits. In Chinese, it is also known as *Baitoushan*, with the same meaning, or *Changbaishan* – "*Chang*" (long), "*bai*" (white), and "*shan*" (mount). The boundary between PRC and DPRK bisects the summit crater lake, Lake

Tianchi (in Chinese sources), or Lake Chon or Chonji (in Korean sources; see Ri, 1993) (Figure 3). The highest point of the caldera rim is 2744 m (in some references, 2750 m) above sea level (a.s.l.). The DPRK side of caldera is generally the higher (Figure 3) with several peaks, including Sangmujigae (2628 m), Hyangdo (2712 m), Janggun (ca. 2750 m), Haebal (2727 m), Tangyol (2593), Jebi (2593) and Ragwon (2606 m) (Figure 3). Lake Tianchi is situated around 450–500 m below the caldera rim, at an elevation of around 2650 m. The irregularly-shaped lake is roughly 4.5 km × 3 km across and about 300 m deep.

Several evolutionary stages have been recognized on the volcano, which lies within the larger Miocene basaltic plateau of Changbaishan (e.g., Wei et al., 2003, 2013; Sakhno, 2007): (i) a Miocene-Early Pleistocene shield-forming stage with alkali and subalkali basaltic lavas (Popov et al., 2008); (ii) a cone-construction (stratovolcano) stage with alkaline lavas and pyroclastic rocks (trachytes, alkalic trachydacites, pantellerites and comendites) (age of 1.12–0.135 Ma); (iii) an ignimbrite-forming stage (up to the present). Paektusuan is renowened for the so-called Millennium Eruption of AD 946 (Oppenheimer, 2011; Oppenheimer et al., 2017), which ejected an estimated 24 km^3 of dense magma (Horn and Schmincke, 2000), mostly as rhyolitic (comendite) tephra but with a subordinate quantity of trachyte. The associated tephra (see Figure 3, inset: “Quaternary pumice”) is represented in a thick sequences of fall and flow deposits on the volcano’s slopes, and is found in marine, terrestrial and lacustrine sites towards and in Japan (e.g. Horn and Schmincke, 2000; McLean et al., 2016).

The Middle Pleistocene-to-Holocene stratigraphy of Paektusan is being assembled through numerous efforts focused on proximal, marine and distal tephra records and is somewhat in flux (e.g., Pan et al., 2017). In the caldera outcrops, the pumices alternate with trachyte flows that build up the main edifice. The silicic rocks occur as glassy lava flows and sheets, as well as ignimbrite, glass tuffs and pumice. Ignimbrites contain *fiammé* and intercalated layers of volcanic glass with phenocrysts and rock fragments; the glassy varieties also contain abundant phenocrysts. One challenge in establishing the stratigraphy arises from the geochemical similarity of discrete units. Nevertheless, recent tephrochronological exercises focused on the distal record identify explosive eruptions at ca. 85.8, 67.6, 61.1 and 50.6 ka (Lim et al., 2013) and ca. 8200‒8100 cal BP (McLean et al., 2018). The eruptive record since the Millennium Eruption has also been uncertain. Some studies (e.g., Sun et al., 2017) recognize a number of post-Millennium Eruption events, but Pan et al. (2017) dispute the stratigraphic evidence for them.

2.2. An overview on obsidian from the Paektusan area

To the best of our knowledge, the first information on obsidian from Paektusan was obtained by the Russian geologist Eduard E. Anert, who participated in the exploration of Manchuria and neighboring regions in 1897 (Anert, 1904). He described black trachytic glass occurring on what is now the DPRK side of the caldera rim (Anert, 1904: 275); precise coordinates were not given, however. Investigations of volcanoes in Manchuria, including Paektusan("Chang-pai-shan" in Japanese sources), by Japanese scholars during the first half of twentieth century, did not report obsidian (e.g., Ogura, 1969: 397–402). In 1958, Soviet and DPRK geologists studied Paektusan and confirmed the occurrence of "lenses of obsidian trachytes" from 15–20 cm to 2 m in thickness in the upper part of the caldera (Denisov and Ten, 1966: 6).

The most complete data on igneous geology of Paektusan prior to the turn of the millennium was published in the "Geology of Korea" (Paek et al., 1993). It is based on geological mapping (scale 1:200,000) conducted by DPRK geologists in 1960–1961, and subsequent investigation. According to Ri (1993), obsidian is found in rocks of the Chonji Formation, consisting of volcaniclastics (brecciated lava, welded breccia, and tuffaceous breccia). The most representative sections of this formation are observed on Janggun and Hyangdo Peaks on the caldera rim (Figure 3). The reference to "trachytic obsidian or tuff" (Ri, 1993: 334) is noteworthy because it is similar to "obsidian trachyte" *sensu* Denisov and Ten (1966) (see Figure 4, A); "rhyolitic obsidian" and "trachydacitic obsidian" are also described. The age of the obsidian-bearing formation was reported as younger than ca. 570 ka (Ri, 1993: 337).

2.3. Recent obsidian studies in the Paektusan area

Following recognition of the PNK1 group in archaeological assemblages from the southern Russian Far East in the late 1990s (e.g. Kuzmin et al., 2002), the need for additional work on Paekusan became evident. Some of the authors visited the Chinese side of Paektusan in 2002, 2004 and 2007, and collected samples of volcanic glass and other rocks on the northern and western parts of the caldera rim (Figure 3). The rocks contain volcanic glass: (i) fragments of trachytic obsidian (PNK-3 group, see below), and trachydacitic and comenditic obsidians; these are embedded in porous pumice, often with abundant phenocrysts; (ii) glassy pantellerite and comendite lavas (or comenditic pitchstone) with abundant phenocrysts (PNK-2 group, see below); (iii) lenses of massive glass within the ignimbrites, with mineral inclusions; and (iv) apparent outcrops of glassy peralkaline rhyolitic and trachytic lavas on the DPRK side of the caldera (see Figure 4, A).

This led to establishment of two geochemical groups of volcanic glass, PNK2 and PNK3 (see Table 1 and Figure 5); the former represented by comenditic rhyolites, and the latter by alkali trachydacites. PNK2 obsidian contains abundant mineral inclusions and as a result does not fracture conchoidally, and for this reason it was rarely exploited by prehistoric humans compared with PNK1. PNK3 obsidian is often pumicieous, with abundant large phenocrysts, and is unsuitable for tool manufacture.

PNK1 obsidian is a peralkaline rhyolite. Judging from the appearance of PNK1 obsidian artifacts found at sites in Primorye (Russia), it is usually black with moderate lustre, exhibiting conchoidal fracture, expressed by transverse (to cleavage) hatching, and with slightly transparent thin edges. Other kinds of archaeological obsidian with the PNK1 signature were identified in Primorye, with strong glassy lustre, conchoidal fracture with smooth surface, slightly transparent thin edges, and longitudinal and transverse hatching (Figure 6, nos. 2–3). Yet another kind is represented by artifacts from the southern part of Primorye. It is dark grey, has moderate glassy lustre, conchoidal fracture, transparent in thick edges, and with small vesicles and mineral inclusions (Figure 6, nos. 5–6). This diversity suggests that the "geological" source of PNK1 artifacts may be distributed spatially, calling to mind the nature of obsidian sources on Hokkaido (Wada et al., 2014).

Further geochemical characterization of obsidian artifacts has been carried out since the year 2000. Popov et al. (2005) analyzed obsidian flakes from two Upper Paleolithic sites in the central part of the Korean Peninsula (in the Republic of Korea, a.k.a. South Korea), Janghung-ri and Hahwagye-ri; this was found to correspond to PNK1 and PNK2 groups. The distance between these sites and Paektusan is about 500 km. Kim et al. (2007), Lee and Kim (2015), and Chang and Kim (2018) analyzed further obsidian artifacts from several Upper Paleolithic and Neolithic sites in South Korea, corroborating the earlier work, and indicating that PNK1 represents the dominant obsidian raw material, with PNK2 a subsidiary material in central and southern parts of the Korean Peninsula (see also Hong 2016). Obsidian artifacts belonging to PNK1 and PNK2 groups were also identified in Manchuria, near Paektusan (Jia et al., 2010, 2013).

3. Methods and materials

3.1. Analytical methods used in this study

The Neutron Activation Analysis (NAA) of obsidian and volcanic glasses (both 'geological" and 'archaeological' samples) from Northeast Asia that we report here were made at the Archaeometry Laboratory, University of Missouri Research Reactor Center (MURR), in Columbia, MO (USA). The methodology has already been described (e.g. Glascock et al., 1998; Glascock et al., 2007: 346; Glascock et al., 2011: 1835–1836), and we refer to these works for additional details. The standard reference material (SRM) used for all obsidian analyses performed at the Archaeometry Laboratory, MURR, is SRM-278 "Obsidian Rock" issued by the National Institute of Standards and Technology (NIST). This SRM is ideal for NAA measurements of obsidian artifacts and geological materials because the concentrations for more than 30 elements are certified by NIST (see Graham et al., 1982). In total, 28 chemical elements were measured (Table 1). The statistical analysis of results obtained was accomplished with the help of software written in GAUSS (see Glascock et al., 1998). It is important from the point of view of methodology that all the measurements were performed in one laboratory using the same analytical standards, and all the results are directly comparable.

Potassium-argon (K–Ar) dating of two obsidian samples, Chongjin and P-8A, was conducted by the CF–GC–IRMS method (Ignatiev et al. 2009). Measurements were performed at the Analytical Center of the Far Eastern Geological Institute, Vladivostok, Russia. Samples were crushed and sieved, and argon was extracted by heating with a continuous infrared laser, and then separated in a helium flow through a chromatographic capillary column. It was transported via a flow divider into the ion source of a Finnigan MAT-253 mass spectrometer. Measurements of the ^{36}Ar, ^{38}Ar, and ^{40}Ar concentrations were performed in the dynamic mode, using an ion detector with three collectors and three electrometric amplifiers (Budnitskiy et al., 2013). The determination of f radiogenic Ar abundance has an error of about 3% at the 2-sigma confidence level. The proportion of atmospheric Ar varies within 5–10% for fine-grained crystalline and volcaniclastic rocks, and 40–50% for glassy rhyolites. The amount of K was analyzed by flame photometry, with an analytical error of 2% at the 2-sigma confidence level. The overall error is 5% and was minimized through repeated measurements and comparison with reference samples. On average, 10–15 measurements were made on each sample.

One sample, K-13, was dated at the Laboratory of Isotope Geochemistry and Geochronometry of the Institute of Geology of Ore Deposits, Russian Academy of Sciences, in Moscow, Russia, using a MI-1201 IG mass spectrometer, by isotope dilution and using ^{38}Ar as a tracer. Flame spectrophotometry was used to determine K content.

The decay constants and ^{40}K content used in the age calculations are: $\lambda_e = 0.581 \times 10^{-10}$ year^{-1}; $\lambda_\beta = 4.962 \times 10^{-10}$ year^{-1}; and $^{40}K/K = 1.167 \times 10^{-4}$ atom % (Steiger and Jäger, 1977). Analytical results are reported in Table 2.

3.2. The Chongjin obsidian sample

The focus of our study is an obsidian boulder acquired in 2004 by M-Y. Hong from Japanese archaeologists. Its dimensions are 19.8 cm × 18.0 cm × 11.5 cm, and it has a mass of

4.4 kg (Figure 7A). It was accompanied with a message stating that a Japanese trading company, Materisk Ltd. of Sakaiminato, Tottori Prefecture, found several obsidian boulders in a storehouse where they kept construction materials imported from DPRK. These boulders, according to the trader, were collected from a river bed in the Chongjin area of DPRK. They were abandoned because the manufacturer (of insulation materials) preferred to use perlite (volcanic glass with abundant phenocrysts), and the obsidian was donated to local archaeologists, who used it for practicing tool manufacture (see Kim, 2014). We refer to this sample as "Chongjin".

4. Results: geochemistry and geochronology of the Chongjin sample

The Chongjin obsidian is black, has a strong glassy lustre, conchoidal fracture with transverse (to cleavage) hatching, and has transparent thin edges of brownish colour. Scanning electron microscopy (Figure 7B) revealed well-developed hatching, fractures and mineral inclusions in otherwise homogeneous glass. Study under optical microscope (Figure 7C) revealed a fluidal-stripy texture due to intercalation of transparent and light grey zones with mineral inclusions.

Geochemical analysis by NAA demonstrates that the Chongjin obsidian belongs to the PNK1 group (Table 1). K–Ar dating of this obsidian yields an age of 1.34 Ma (Table 2). The dating of an obsidian artifact from the Timofeevka 1 site in southern Primorye, also belonging to PNK1 (see Kuzmin et al., 2002), yielded an age of ca. 1.25 Ma (Table 2, sample P-8A). The minor difference could be due to partial loss of radiogenic Ar in the archaeological sample, e.g. by exposure to fire or boiling water, and we consider these two ages to be compatible with a single source.

Based on the age and geochemical composition of the Chongjin obsidian, it is clearly not associated with the PNK2 and PNK3 groups that have been investigated on the Chinese side of Paektusan. Comparing the age of the Chongjin sample with the rock record for Paektusan is not straightforward due to the lack of a coherent edifice-wide stratigraphy. From Wei et al. (2003, 2013) and Sakho (2007), rocks of this age fall within the 'Cone Construction' stage of Changbaishan's activity, with trachyandesites and trachytes belonging to the Xiaobaishan formation and dated to ca. 1–1.49 Ma. According to Yun et al. (1993), only alkali olivine basalts were erupted between ca. 1.7–2.9 Ma and ca. 96–650 ka. The composition of the Late Pliocene alkali rhyolites reported by Yun et al. (1993) differs from the subalkaline obsidian of the PNK1 type. Closer to PNK1 in the content of alkalis and dominance of K_2O over Na_2O are rhyolites in a bimodal alkali basalt-rhyolite series from Wangtian Volcano, 30 km SW of the Paektusan (Fan et al., 1999). However, these rocks are dated to ca. 2.12–2.67 Ma (Fan et al., 1999).

5. Discussion and conclusions – towards locating the provenance of PNK1 obsidian

We believe that the primary source of the PNK1 obsidian should be relatively conspicuous, with outcrops accessible to ancient people from the Paleolithic to the Bronze Age (ca. 3.5–25 ka). One candidate could be obsidian found near the caldera rim of Paektusan, with first indications by Anert (1904) and Denisov and Ten (1966), and subsequently by DPRK geologists (see Ri, 1993). Citing Inomata (2002), Jia et al. (2013: 976–977) suggested that the primary source of the PNK1 obsidian is located on the caldera rim or just to the south at the headwaters of the Yalu River in DPRK. However, considering the data available to us, PNK1 is not represented amongst the volcanic glasses collected on the Chinese side of the caldera, and we doubt that the "obsidian trachyte", "rhyolitic obsidian" or "trachydacitic obsidian" *sensu* Denisov and Ten (1966) and Ri (1993) can be the primary source. It is more likely that these rocks contain the PNK2 obsidian, identified on and around the caldera rim (see Popov et al., 2005; Kim, 2014), which is represented in archaeological collections of the Russian Far East, Korean Peninsula, and Manchuria, albeit in relatively small quantities compared with PNK1 lithics.

One potential source for PNK1 might be associated with the Pliocene to early Pleistocene volcanism of the Kilju–Myongchon region (around Hwasong and Myongchon, see Figures 1 and 8), notably the rocks (predominantly alkali rhyolites) of the Chilbosan Group (Kim and Pak, 1993). The Hyangrobong Formation of the Chilbosan Group includes rhyolites, perlites or pitchstones, and obsidians (Kim and Pak, 1993: 324). This region is around 100 km south of the Chongjin City area, from where our Chongjin sample is thought to have originated (Figure 1). However, the K–Ar dating of sub-alkali rhyolite from Kilju–Myongchon region yielded an age of 5.28 ± 0.14 Ma (Table 2, sample K-13). It is possible that this sample represents an earlier phase of volcanism in the region, e.g., the Musudan Formation of the Chilbosan Group (Kim and Pak, 1993: 324). At least for the time being, however, there is no strong evidence to support locating the PNK1 source in the Kilju–Myongchon region.

Another potential source for geological obsidians is the area of volcanoes situated some 40–50 km southeast of Paektusan (see Figure 8). These include silicic rocks (Paek et al., 1993) indicated on the geological map of Wang et al. (2003), which shows acidic effusives (pantellerites) near Nanbaotai (Nampotaesan) Volcano. This corresponds to the field of trachytes and trachydacites between Hwangbong and Phurunbong volcanoes (Ri, 1993: 331–332) (see Figure 8). Unfortunately, chemical data for these rocks are not reported.

Yi and Jwa (2016) also acquired obsidian from the DPRK through a mineral dealer in China, who claimed that it was mined in the Paektusan region (S. Yi, pers. comm., June 2016). In their Figure 1 (Yi and Jwa, 2016: 38), they show locations for several samples to the southeast of Paektusan, some in the Nanbaotai area, another up to 90 km from Paektusan near the town of Paegam in Ryanggang. Unfortunately, the small number of elements analyzed by Yi and Jwa (2016) and using LA-ICP–MS, precludes a detailed comparison with our NAA results (Table 1). However, for those elements that are common to our datasets (La, Ce, Pr, Nd, Sm, Gd, Dy, Er and Yb), there is a close correspondence with the Chongjin sample and PNK-1, especially for a subset of the Yi and Jwa (2016) samples with slightly higher trace element abundances.

While we have found further evidence locating the provenance of PNK1 obsidian in the DPRK in form of “geological” sample called Chongjin, we fully understand that only future fieldwork in the country can completely solve the “puzzle”. International collaborations are building with DPRK geoscientists (e.g., Iacovino et al., 2016; Ri et al., 2016; see also Stone, 2013) and we are optimistic that the source will ultimately be identified.

Acknowledgments

We are grateful to the following colleagues who assisted in the preparation of the original manuscript: to N.A. Kluyev, O.L. Moreva and N.A. Dorofeeva (Institute of History, Archaeology and Ethnography of the People of the Far East, Far Eastern Branch of the Russian Academy of Sciences, Vladivostok, Russia) for permission to photograph obsidian artifacts from their collections; to V.T. Syedin (Pacific Oceanographic Institute, Far Eastern Branch of the Russian Academy of Sciences, Vladivostok) and V.A. Lebedev (Institute of Geology of the Ore Deposits, Russian Academy of Sciences, Moscow, Russia) for collection and dating of the K-13 obsidian; and to A.K. Konopatsky (General Military Academy, Novosibirsk, Russia) for providing obsidian samples acquired in DPRK, which initiated our research on this question. This study has been supported, since 2002, by grants from the U.S. Civil Research and Development Foundation (RG1-2538-VL-03 and RUG1-7097-NO-13); U.S. NSF (NSF-1415403); the Japan Society for Promotion of Science; the Tomsk State University Competitiveness Improvement Program; and the Russian Foundation for Basic Sciences (RFFI) (18-35-00180 mol-a).

References

Anert, E.E., 1904. Puteshestvie po Manchzurii [À Travers la Mandjourie] (Memoirs of the Imperial Russian Geographic Society on General Geography. Vol. XXXV). St.-Petersburg: Imperatorskoe Russkoe Geograficheskoe Obshchestvo. In Russian.

Budnitskiy, S.Y, Ignatiev, A.V., Velivetskaya, T.A., 2013. Method for measurement of argon isotopes in helium flow for K/Ar geochronology. Mineral. Mag. 77, 788.

Cann, J.R., 1983. Petrology of obsidian artefacts. In: Kempe, D.R.C., Harvey, A.P. (Eds.), The Petrology of Archaeological Artefacts. Clarendon Press, Oxford, pp. 227–255.

Cann, J.R., Renfrew, C., 1964. The characterization of obsidian and its application to the Mediterranean region. Proc. Prehist. Soc. 30, 111–133.

Carter, T., 2014. The contribution of obsidian characterization studies to early prehistoric archaeology. In: Yamada, M., Ono, A. (Eds.), Lithic Raw Material Exploitation and Circulation in Prehistory. University of Liege, Liege, pp. 25–35.

Chang, Y., Kim, J.-C., 2018. Provenance of obsidian artifacts from the Wolseongdong Paleolithic site, Korea, and its archaeological implications. Quat. Int. 467, 360–368.

Denisov, E.P., Ten H.C., 1966. Kratkaya Geologicheskaya Kharakteristika Vulkana Pektusan (Baitoushan) [The Short Geological Characteristic of Paektusan (Baitoushan) Volcano]. Vladivostok: Dalnevostochnoe Knizhnoe Izdatelstvo (Supplement Brochure to: Khudyakov, G.I. (Ed.). 1965. Voprosy Geomorfologii i Morfotektoniki Yuzhnoi Chasti Dalnego Vostoka [Questions on Geomorphology and Morphotectonics of the Southern Part of the Far East]. Vladivostok: Dalnevostochnoe Knizhnoe Izdatelstvo). In Russian.

Doelman, T., Torrence, R., Popov, V., Ionescu, M., Kluyev, N., Sleptsov, I., Pantyukhina, I., White, P., Clemens, M., 2008. Source selectivity: an assessment of volcanic glass sources in the southern Primorye, Far East Russia. Geoarchaeology 23, 243–273.

Doelman, T., Torrence, R., Popov, V., Kluyev, N., Sleptsov, I,. 2012. Volcanic glass procurement and use in the Late Paleolithic, central Primorye, Far East Russia. In: Liritzis, J., Stevenson, C.M. (Eds.), Obsidian and Ancient Manufactured Glass. University of New Mexico Press, Albuquerque, NM, pp. 97–114.

Fan, Q., Liu, R., Li, D., Li, Q., 1999. Significance of K–Ar age of bimodal volcanic rocks at Wangtian'e Volcano, Changbaishan area. Chinese Sci. Bull. 44, 660–663.

Fedorchuk, A.V., Filatova, N.I., 1993. Cenozoic volcanic rocks of North Korea and the geodinamic environtments of their formatiom. Petrology 1, 645–656. In Russian with English abstract.

Garin-Michailowski, N.G., 2005. Koreas Schlafender Vulkan. Die Reise zum Pektusan. Lenningen, Edition Erdmann.

Glascock, M.D., Braswell, G.E., Cobean, R.H., 1998. A systematic approach to obsidian source characterization. In: Shackley, M.S. (Ed.), Archaeological Obsidian Studies: Method and Theory. Plenum Press, New York & London, pp. 15–65.

Glascock, M.D., Speakman, R.J., Neff, H., 2007. Archaeometry at the University of Missouri Research Reactor and the provenance of obsidian artefacts in North America. Archaeometry 49, 343–367.

Glascock, M.D., Kuzmin, Y.V., Grebennikov, A.V., Popov, V.K., Medvedev, V.E., Shewkomud, I.Y., Zaitsev, N.N., 2011. Obsidian provenance for prehistoric complexes in the Amur River basin (Russian Far East). J. Archaeol. Sci. 38, 1832–1841.

Graham, C.C., Glascock, M.D., Carni, J.J., Vogt, J.R., Spalding, T.G., 1982. Determination of elements in the National Bureau of Standards' geological standard reference materials by Neutron Activation Analysis. Analyt. Chem. 54, 1623–1627.

Hong, M.-Y., 2016. Obsidian use in Paleolithic industries on the Korean Peninsula. In: Choi, M.-R. (Ed.), Segyesa Sokeseoeu Hangook. Seoul: Juluesung Publ., pp. 109–140. In Korean with English abstract.

Horn, S., Schminke, H.-U., 2000. Volatile emission during the eruption of Baitoushan Volcano (China/North Korea) ca. 969 AD. Bull. Volcanol. 61, 537–555.

Iacovino, K., Ju-Song, K., Sisson, T., Lowenstern, J., Kuk-Hun, R., Jong-Nam, J., Kun-Ho, S., Song-Hwan, H., Oppenheimer, C., Hammond, J.O.S., Donovan, A., Liu, K.W., Kum-Ran, R., 2016. Quantifying gas emissions from the "Millennium Eruption" of Paektu Volcano, Democratic People's Republic of Korea/China. Sci. Adv. 2, e16009132.

Ignatiev, A.V., Velivetskaya, T.A., Budnitskiy, S.Y., 2009. A continuous flow mass spectrometry technique of argon measurement for K/Ar geochronology. Rapid Comm. Mass Spectrom. 23, 2403–2410.

Inomata, M., 2002. Paektusan Chonji. Geol. Soc. Japan News 3(9), 2–3. In Japanese.

James, H.E.M., 1888. The Long White Mountain, or Journey in Manchuria: with Some Account of the History, People, Administration and Religion of that Country. Longmans, Green & Co., London.

Jia, P.W., Doelman, T., Chen, C., Zhao, H., Lin, S., Torrence, R., Glascock, M.D., 2010. Moving sources: a preliminary study of volcanic glass artifact distributions in Northeast China using pXRF. J. Archaeol. Sci. 37, 1670–1677.

Jia, P.W., Doelman, T., Torrence, R., Glascock, M.D., 2013. New pieces: the acquisition and distribution of volcanic glass sources in Northeast China during the Holocene. J. Archaeol. Sci. 40, 971–982.

Khain, V.E., 1994. Geology of Northern Eurasia (Ex-USSR). Part 2. Phanerozoic Fold Belts and Young Platforms. Gebrüder Borntraeger, Berlin & Stuttgart.

Kim, H.S., Pak, I.S., 1993. Meso-Cenozoic volcanism. In: Paeк, R.J., Gap, K.H., Jon G.P., (Eds.), Geology of Korea. Foreign Languages Books Publishing House, Pyongyang, pp. 313–330.

Kim, J.-C., 2014. The Paektusan Volcano source and geochemical analysis of archaeological obsidians in Korea. In: Ono, A., Glascock, M.D., Kuzmin, Y.V., Suda, Y. (Eds.), Methodological Issues for Characterisation and Provenance Studies of Obsidian in Northeast Asia. Archaeopress, Oxford, pp. 167–178.

Kim, J.-C., Kim, D.K., Yoon, M., Yun, C.C., Park, G., Woo, H.J., Hong, M.-Y., Lee, G.K., 2007. PIXE provenancing of obsidian artefacts from Paleolithic sites in Korea. Bull. Indo-Pacific Prehist. Assoc. 27, 122–128.

Kuzmin, Y.V., 2014. Geoarchaeological aspects of obsidian source studies in the southern Russian Far East and brief comparison with neighbouring regions. In: Ono, A., Glascock, M.D., Kuzmin, Y.V., Suda, Y. (Eds.), Methodological Issues for Characterisation and Provenance Studies of Obsidian in Northeast Asia. Archaeopress, Oxford, pp. 143–165.

Kuzmin, Y.V. 2017. Obsidian as a commodity to investigate human migrations in the Upper Paleolithic, Neolithic, and Paleometal of Northeast Asia. Quat. Internat. 442B, 5–11.

Kuzmin, Y.V., Glascock, M.D., 2014. The Neutron Activation Analysis of volcanic glasses in the Russian Far East and neighbouring Northeast Asia: a summary of the first 20 years of research. In: Ono, A., Glascock, M.D., Kuzmin, Y.V., Suda, Y. (Eds.), Methodological Issues for Characterisation and Provenance Studies of Obsidian in Northeast Asia. Archaeopress, Oxford, pp. 85–93.

Kuzmin, Y. V., Popov, V.K. (Eds)., 2000. Volcanic Glasses of the Russian Far East: Geological and Archaeological Aspects. Far Eastern Geological Institute, Vladivostok. In Russian with English abstract.

Kuzmin, Y.V., Popov, V.K., Glascock, M.D., Shackley, M.S., 2002. Sources of archaeological volcanic glass in the Primorye (Maritime) Province, Russian Far East. Archaeometry 44, 505–515.

Lee, G.K., Kim, J.-C., 2015. Obsidians from the Sinbuk archaeological site in Korea – evidences for strait crossing and long-distance exchange of raw material in Paleolithic Age. J. Archaeol. Sci.: Reports 2, 458–466.

Lim, C., Toyoda, K., Ikehara, K., Peate, D.W., 2013. Late Quaternary tephrostratigraphy of Baegdusan and Ulleung volcanoes using marine sediments in the Japan Sea/East Sea. Quat. Res. 80, 76–87.

Macdonald, R., Smith, R.L., Thomas, J.E.. 1992, Chemistry of the Subalkalic Silicic Obsidians (U.S.G.S. Professional Paper 1523). U.S. Geological Survey, Boulder, CO.

McLean, D., Albert, P.G., Nakagawa, T., Staff, R.A., Suzuki, T. Smith, V.C., 2016. Identification of the Changbaishan ‘Millennium’(B-Tm) eruption deposit in the Lake Suigetsu (SG06) sedimentary archive, Japan: synchronisation of hemispheric-wide palaeoclimate archives. Quat. Sci. Rev. 150, 301–307.

McLean, D., Albert, P.G., Nakagawa, T., Suzuki, T., Staff, R.A., Yamada, K., Kitaba, I., Haraguchi, T., Kitagawa, J., Smith, V., 2018. Integrating the Holocene tephrostratigraphy for East Asia using a high-resolution cryptotephra study from Lake Suigetsu (SG14 core), central Japan. Quat. Sci. Rev. 183, 36–58.

Ogura, T., 1969. Volcanoes in Manchuria. In: Ogura, T. (Ed.), Geology and Mineral Resources of the Far East, Vol. 2. Tokyo Geographical Society, Tokyo, pp. 373–413.

Ono, A., 1976. Koki kyusekki jidai no shudan kankei [The group relationship in the Late Paleolithic]. Kokogaku Kenkyu 23, 9–22. In Japanese.

Oppenheimer, C., 2011. Eruptions that Shook the World. Cambridge University Press, Cambridge.

Oppenheimer, C., Wacker, L., Xu, J., Galván, J.D., Stoffel, M., Guillet, S., Corona, C., Sigl, M., Di Cosmo, N., Hajdas, I., Pan, B., Breuker, R., Schneider, L., Esper, J., Fei, J., Hammond, J.O.S., Büntgen, U., 2017. Multi-proxy dating the ‘Millennium Eruption’ of Changbaishan to late 946 CE. Quat. Sci. Rev. 158, 164–171.

Paeк, R.J., Gap, K.H., Jon, G.P. (Eds.), 1993. Geology of Korea. Foreign Languages Books Publishing House, Pyongyang.

Pan, B., de Silva, S.L., Xu, J., Chen, Z., Miggins, D.P., Wei, H., 2017. The VEI-7 Millennium eruption, Changbaishan-Tianchi volcano, China/DPRK: new field, petrological, and chemical constraints on stratigraphy, volcanology, and magma dynamics. J. Volcanol. Geotherm. Res. 343, 45–59.

Park, Y.-H., Lee, K.-S., Lee, H.-Y., Son, I., Lee, J.-R. (Eds.), 2000. Atlas of Korea. Sungji Munhwa, Seoul.

Pollmann, H.-O., 1999. Obsidian – Bibliographie: Artefakt und Provenienz. Deutsches Bergbau-Museum, Bochum.

Popov, V.K., Sandimirova, G.P., Velivetskaya, T.A., 2008. Strontium, neodymium, and oxygen isotopic variations in the alkali basalt–trachyte–pantellerite–comendite series of Paektusan Volcano. Doklady Earth Sci. 419, 329–334.

Popov, V.K., Solyanik, V.A., Fedoseev, D.G., 2009. Decorative volcanic glasses from hyaloclastites of the Shkotovo Basaltic plateau (Primorye, Russia). J. Gemmol. Assoc. Hong Kong 30, 51–56.

Popov, V.K., Sakhno, V.G., Kuzmin, Y.V., Glascock, M.D., Choi, B.-K., 2005. Geochemistry of volcanic glasses of the Paektusan Volcano. Doklady Earth Sci. 403, 254–259.

Ri, D., 1993. Paektu Volcano. In: Paeк, R.J., Gap, K.H., Jon, G.P. (Eds.), Geology of Korea. Foreign Languages Books Publishing House, Pyongyang, pp. 330–344.

Ri, K.-S., Hammond, J.O.S., Ko, C.-N., Kim, H., Yun, Y.-G., Pak, G.-J., Ri, C.-S., Oppenheimer, C., Kosima, W.L., Iacovino, K., Ryu, K.-R., 2016. Evidence for partial melt in the crust beneath Mt. Paektu (Changbaishan), Democratic People's Republic of Korea and China. Sci. Adv. 2, e1501513.

Sakhno, V.G., 2007. Chronology of eruptions, composition, and magmatic evolution of the Paektusan Volcano: evidence from K–Ar, $^{87}Sr/^{86}Sr$, and $\delta^{18}O$ isotope data. Doklady Earth Sci. 412, 22–28.

Shackley, M.S., 2005. Obsidian: Geology and Archaeology in the North American Southwest. University of Arizona Press, Tucson, AZ.

Skinner, C.E., Tremaine, K.J., 1993. Obsidian: An Interdisciplinary Bibliography. San Jose University. San Jose, CA.

Steiger, R.H., Jäger, E., 1977. Subcommission on geochronology: convention on the use of decay constants in geo- and cosmology. Earth Planet. Sci. Lett. 36, 359–361.

Stephan, J.J., 1994. The Russian Far East: A History. Stanford University Press, Stanford, CA.

Stone, R., 2013. Sizing up a slumbering giant. Science 341, 1060–1061.

Sun, C., Liu, J., You, H., Nemeth, K., 2017. Tephrostratigraphy of Changbaishan volcano, northeast China, since the mid-Holocene. Quat. Sci. Rev. 177, 104–119.

Suzuki, M., 1973. Chronology of prehistoric human activity in Kanto, Japan. Part 2: Time-space analysis of obsidian transportation. J. Faculty Sci., Univ. Tokyo. Section 5 (Anthropol.) 4, 396–469.

Wada, K., Mukai, M., Sano, K., Izuho, M., Sato H., 2014. Chemical composition of obsidians in Hokkaido Island. Northern Japan: the importance of geological and petrological data for sources studies. In: Ono, A., Glascock, M.D., Kuzmin, Y.V., Suda, Y. (Eds.), Methodological Issues for Characterisation and Provenance Studies of Obsidian in Northeast Asia. Archaeopress, Oxford, pp. 95–108.

Wakita, K., 2013. Geology and tectonics of Japanese islands: a review – the key to understanding the geology of Asia. J. Asian Earth Sci. 72, 75–87.

Wang, Y., Li, C., Wei, H., Shan, X., 2003. Late Pliocene–recent tectonic setting for the Tianchi volcanic zone, Changbai Mountains, northeast China. J. Asian Earth Sci. 21, 1159–1170.

Wei, H., G. Liu, J. Gill. 2013. Review of eruptive activity at Tianchi volcano, Changbaishan, northeast China: implications for possible future eruptions. Bulletin of Volcanology 75, 706.

Wei, H., Sparks, R.S.J., Liu, R., Fan, Q., Wang, Y., Hong, H., Zhang, H., Chen, H., Jiang, C., Dong, J., Zheng, Y., Pan, Y., 2003. Three active volcanoes in China and their hazards. J. Asian Earth Sci. 21, 515–526.

Williams-Thorpe, O., 1995. Obsidian in the Mediterranean and Near East: a provenancing success story. Archaeometry 37, 217–248.

Yi, S., Jwa, Y.J., 2016. On the provenance of prehistoric obsidian artifacts in South Korea. Quat. Internat. 392, 37–43.

Yun, S.H., Kwan, W.C., Lee, M.W., 1993. Cenozoic volcanic activity and petrochemistry of volcanic rocks in the Mt. Paektu area. J. Geol. Soc. Korea 29, 291–307.

Figure captions

Figure 1. Regional map of Northeast Asia, highlighting location of Paektusan (after Park et al., 2000; modified).

Figure 2. Distribution of obsidian artifacts of the PNK1 group in Northeast Asia (see text for references).

Figure 3. Geological sketch map of the Paektusan summit area (modified after Ri, 1993; Jia et al., 2013). Sampling points: a –Kim et al. (2007); b –Popov and Kuzmin (2002, 2004, 2007).

Figure 4. (A) View of the DPRK side of the caldera, showing possible layers of trachytic “obsidians” (photo by Y.V. Kuzmin from the Chinese side, July 2002); (B) view of the Chinese side of the caldera, with indication of the headwaters of Erdaobai River (see Figure 3); arrow shows viewpoint of (A) (photo by C. Oppenheimer from DPRK side, August 2015).

Figure 5. Hf–Eu diagram for volcanic glasses of the Paektusan. Geochemical groups: 1 – PNK1; 2 – PNK2; 3 – PNK3; 4 – artifacts; 5 – ‘geological’ obsidian (Chongjin sample).

Figure 6. Obsidians from Northeast Asia. 1 – ‘geological’ obsidian (Chongjin sample); 2–6 – ‘archaeological’ obsidians from Primorye Province: 2 – from Uglovaya Inlet 1 site (collection of N.A. Kluyev); 3 – from Voevoda 2 site (collection of N.A. Dorofeeva); 4 – from from Alekseev-Nikolskoe 1 site (collection of N.A. Kluyev); 5 – from Voevoda 2 site (collection of N.A. Dorofeeva); and 6 – from Luzanova Sopka 3 site (collection of O.L. Moreva).

Figure 7. The Chongjin obsidian. (A) General view (scale in cm); (B) Scanning electron microscope view (white scale bar is 20 μm); and (C) Optical microscope view.

Figure 8. General geology and Cenozoic volcanism of the northern Korean Peninsula (modified after Fedorchuk and Filatova, 1993). 1 – Precambrian to Mesozoic rocks; 2–3 – rocks of the Paektusan–Paegam region: 2 – Quaternary trachytes, alkali and subalkali rhyolites, 3 – Pliocene – Quaternary basalts; 4–5 – rocks of the Kilju–Myongchon region: 4 – Miocene trachytes, alkali and subalkali rhyolites, 5 – basalts; 6 – tectonic faults. Circled numbers, 1 and 2, correspond to the Paektusan–Paegam and Kilju–Myongchon regions, respectively; dashed ellipse indicates the most probable location of the PNK1 primary obsidian source.

Table 1. Comparison of Chongjin sample with PNK1, PNK2 and PNK3 groups (after Kuzmin and Glascock, 2014). Concentrations are in parts-per-million except where reported in percent.

Element	PNK1 (n = 38)			PNK2 (n = 7)			PNK3 (n = 3)			Chongjin obsidian
	mean		s.d.*	mean		s.d.*	mean		s.d.*	
Na (%)	3.07	±	0.09	3.80	±	0.23	4.17	±	0.11	3.00
Al (%)	6.76	±	0.48	5.78	±	0.58	8.19	±	0.25	6.86
Cl	703	±	87	1435	±	671	429	±	53	706
K (%)	4.19	±	0.28	3.89	±	0.31	4.51	±	0.08	4.78
Sc	1.10	±	0.09	1.31	±	0.59	4.66	±	0.72	1.15
Mn	310	±	7	864	±	219	1036	±	32	308
Fe (%)	1.08	±	0.02	2.96	±	0.1	3.70	±	0.06	1.04
Co	0.28	±	0.07	0.21	±	0.13	1.17	±	0.31	0.40
Zn	111	±	138	245	±	9	139	±	15	85
Rb	236	±	9	302	±	28	132	±	5	220
Sr	28	±	6		< 5			< 5		30
Zr	251	±	12	1430	±	313	506	±	19	249
Sb	0.37	±	0.03	0.32	±	0.09	0.15	±	0.01	0.33
Cs	3.90	±	0.16	4.36	±	0.62	1.40	±	0.03	3.62
Ba	102	±	36	50	±	20	61	±	26	117
La	68	±	2	164	±	6	80	±	4	64
Ce	137	±	4	322	±	13	155	±	7	129
Nd	49	±	5	125	±	19	65	±	2	53
Sm	10.86	±	0.5	23.6	±	1.9	11.9	±	0.3	10.4
Eu	0.27	±	0.06	0.33	±	0.03	0.51	±	0.12	0.33
Tb	1.62	±	0.12	3.16	±	0.44	1.48	±	0.01	1.44
Dy	10.3	±	0.8	19.9	±	2.3	8.1	±	0.4	10.3
Yb	4.55	±	0.34	9.02	±	0.78	4.05	±	0.48	4.12
Lu	0.72	±	0.06	1.34	±	0.18	0.56	±	0.03	0.57
Hf	10.0	±	0.3	40.3	±	9.0	14.6	±	0.3	9.4
Ta	6.77	±	0.42	10.5	±	2.7	4.28	±	0.1	6.05
Th	27.5	±	0.9	33.8	±	7.8	5.2	±	0.5	25.6

U	7.1	±	3.0	11.4	±	3.9	5.2	±	0.5	8.6

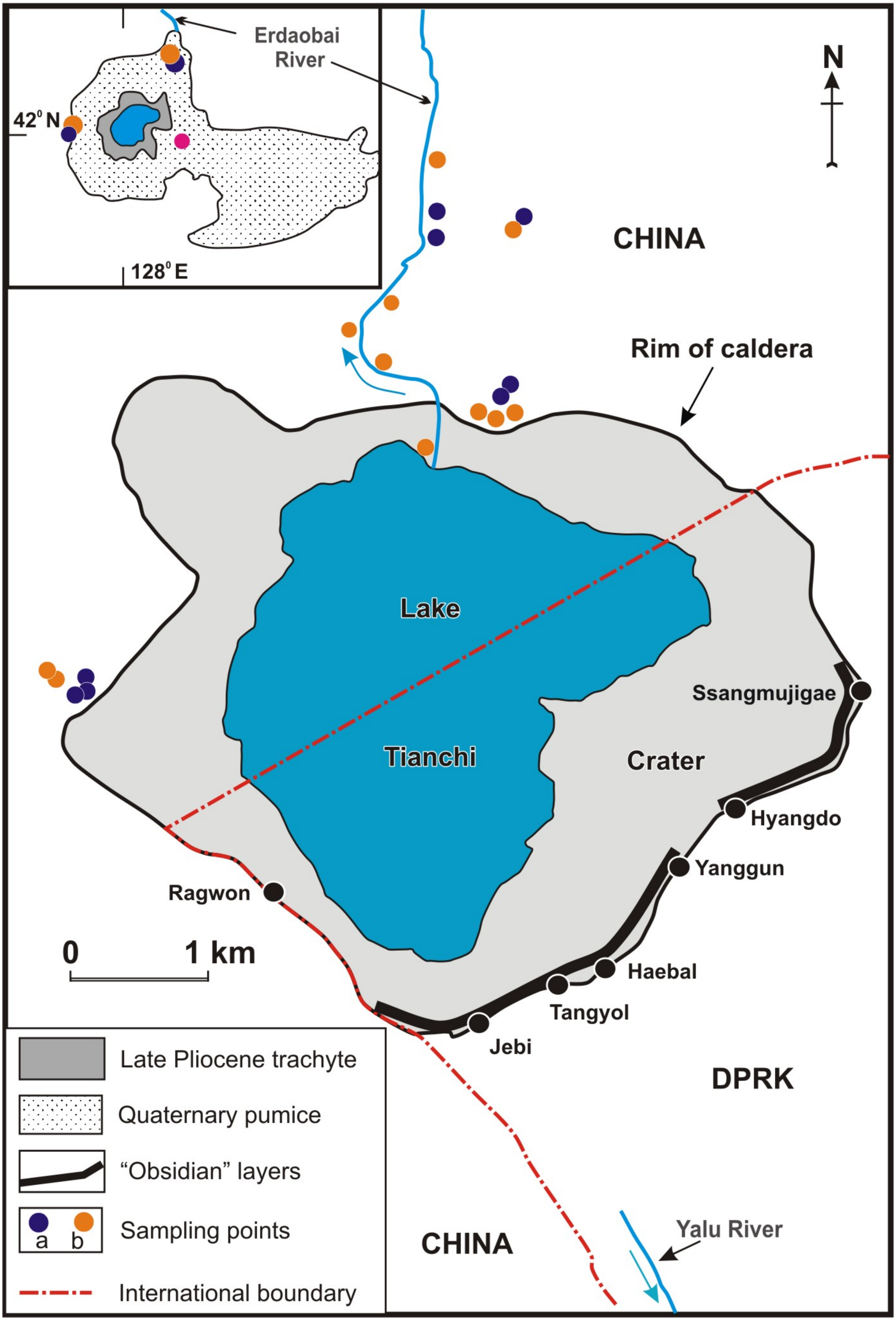
*s.d – standard deviation.

Table 2. Results of K–Ar dating of obsidian and rhyolite from DPRK and the Russian Far East.

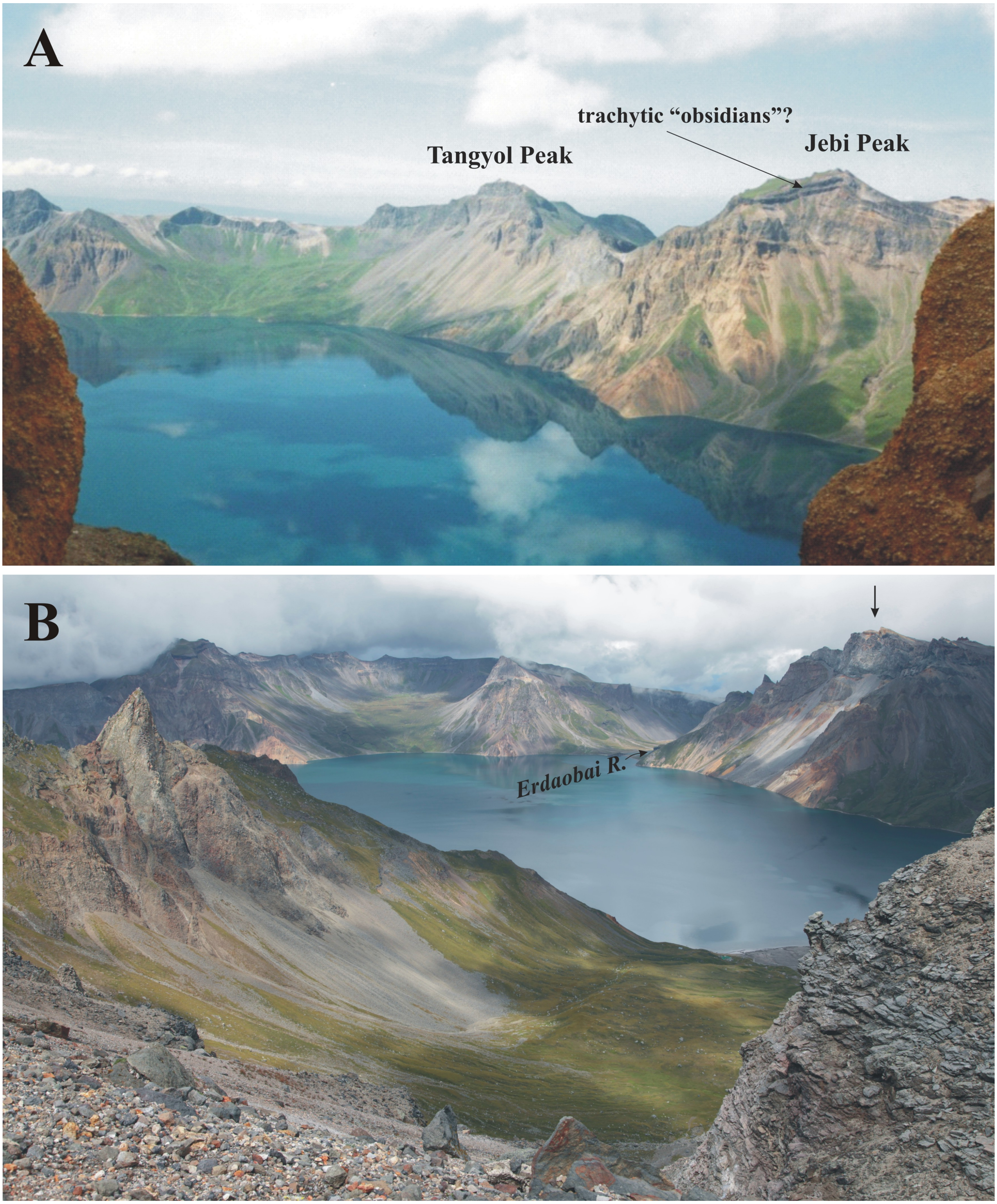
Sample	K, % (± 2σ)	Ar_{air}, %	Ar_{rad}, ng/g (± 2σ)	Age, Ma (± 2σ)
Chongjin	4.5 ± 0.09	46	0.412 ± 0.014	1.34 ± 0.07
P-8A*	4.4 ± 0.09	55	0.354 ± 0.011	1.25 ± 0.06
K-13	5.11 ± 0.06	–	1.873 ± 0.010	5.28 ± 0.14

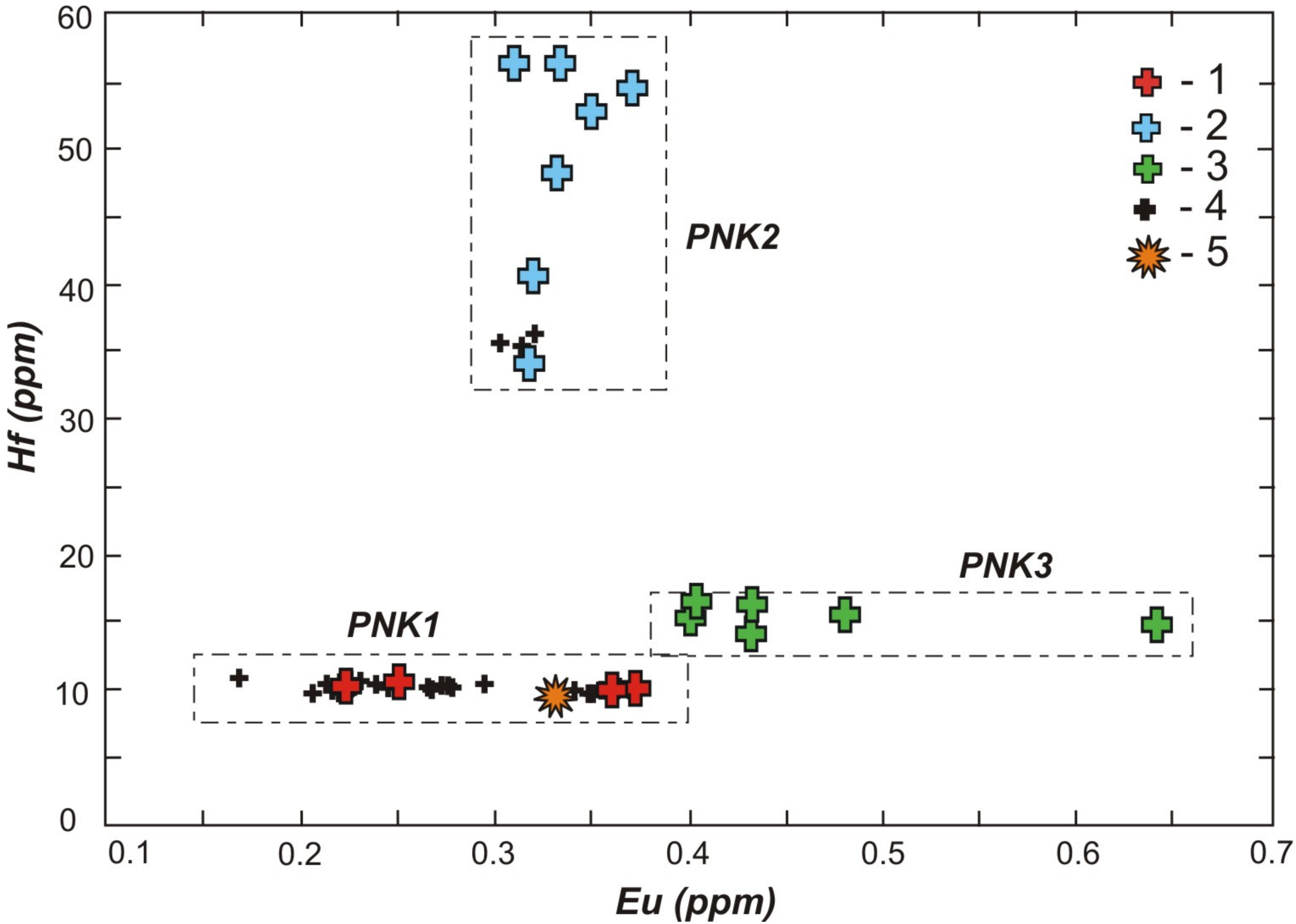
*Artifact from the Timofeevka 1 site, Primorye Province, Russia (see Kuzmin et al. 2002).


enlarged area
CHINA
JILIN
RUSSIA
see the Google Earth view
Paektusan
HAMGYŎNGBUK-DO
YANGGANG-DO
DPRK
Chongjin
Sea of Japan (East Sea)
0
100 km
Yanji
Onsŏng
Hunchun
Helong
Hoeryŏng
Musan
Songjiangha
Kraskino
Pos'yet
Khasan
Ŭndŏk
Sŏnbong (Unggi)
Najin
Puryŏng
Yŏnsa
Samjiyŏn
Paegam
Kyŏngsŏng
Ŏrang
Poch'on
HYESAN
Kimhyŏngjik (Huch'ang)
Kimjŏngsuk (Shinp'a)
Samsu
Unhŭng
Hwasŏng
Kapsan
Myŏngch'on
Nangnim
Hamgyŏngsanmaek
Mach'ŏllyŏngsanmaek
128°
129°
130°
131° E
43° N
42°
F
G
H

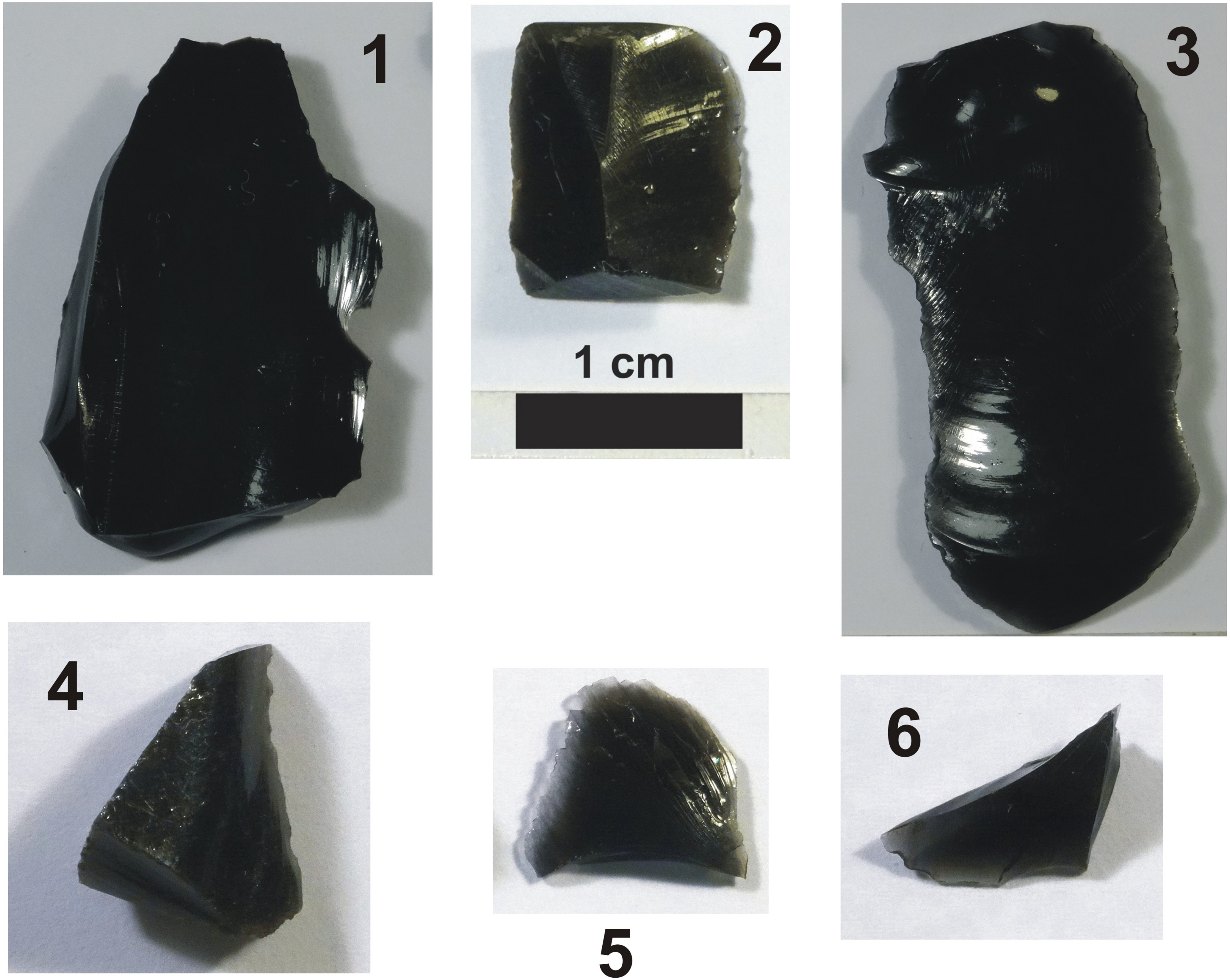


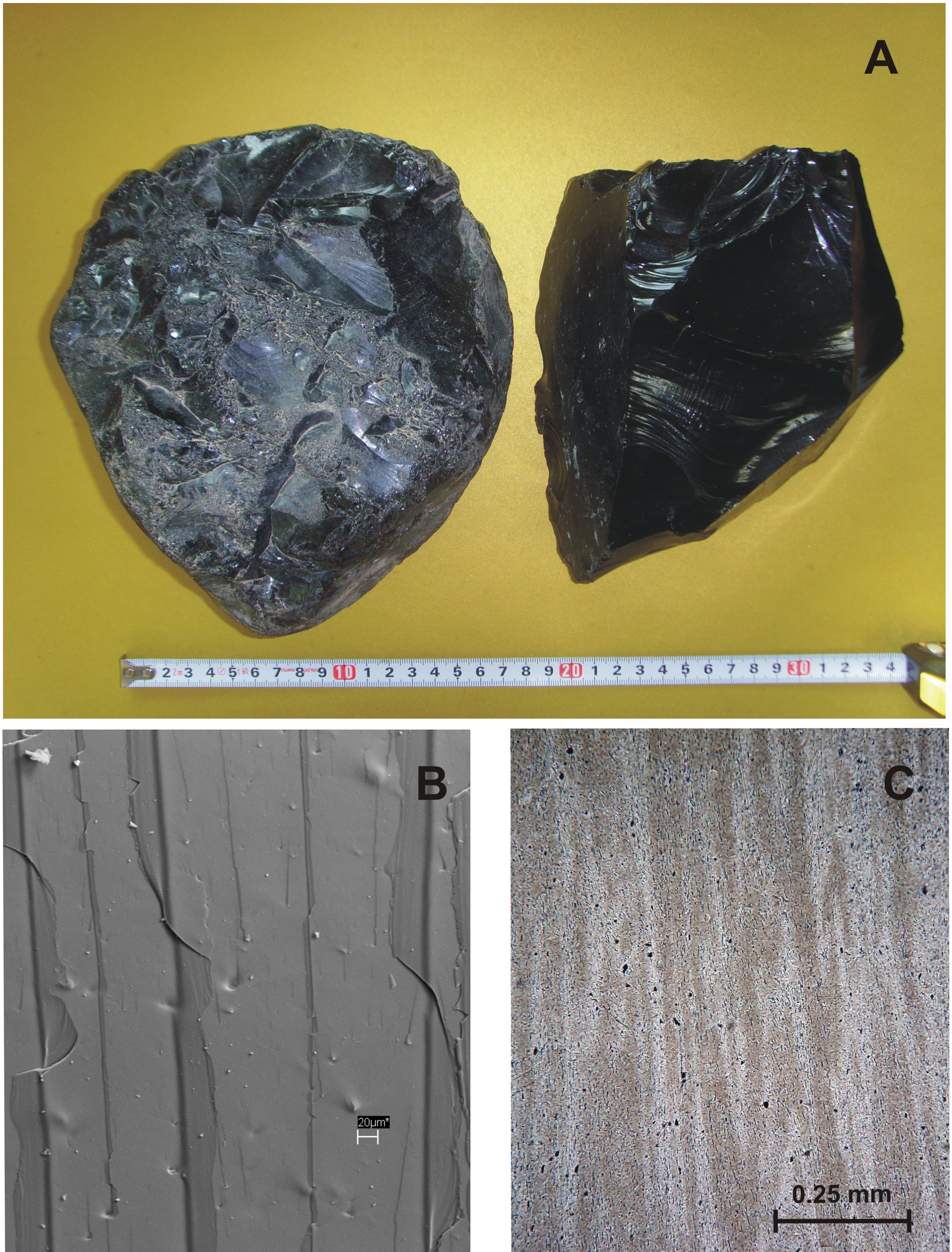
Erdaobai River
42° N
128° E
N
CHINA
Rim of caldera
Lake
Tianchi
Crater
Ssangmujigae
Hyangdo
Yanggun
Haebal
Tangyol
Jebi
Ragwon
0
1 km
DPRK
CHINA
Yalu River
Late Pliocene trachyte
Quaternary pumice
"Obsidian" layers
a
b
Sampling points
International boundary

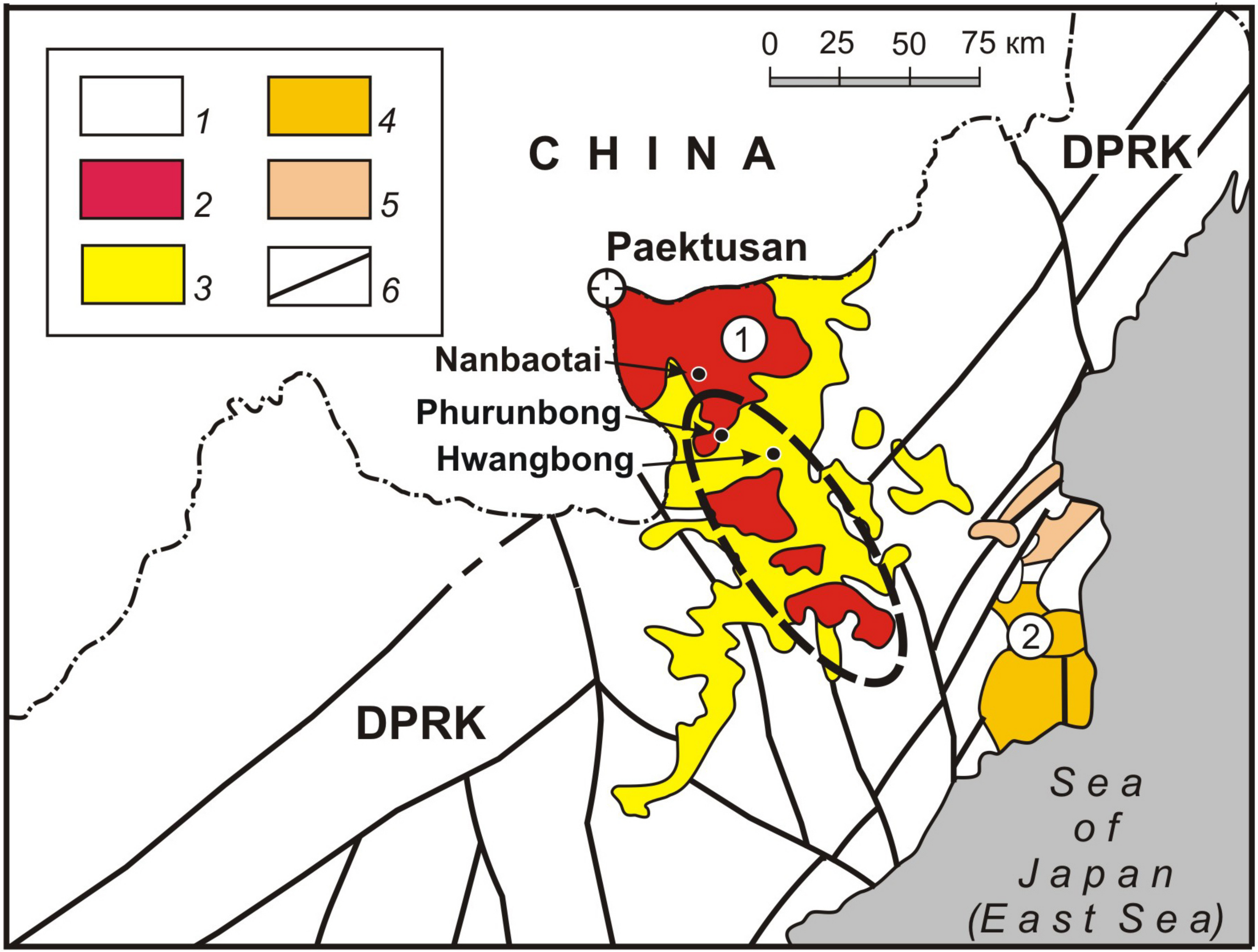

A
trachytic “obsidians”?
Tangyol Peak
Jebi Peak
B
Erdaobai R.



Hf (ppm)
Eu (ppm)
PNK1
PNK2
PNK3
- 1
- 2
- 3
- 4
- 5
0
10
20
30
40
50
60
0.1
0.2
0.3
0.4
0.5
0.6
0.7


1
2
1 cm
3
4
5
6


A
B
20µm*
C
0.25 mm



0 25 50 75 км
1
2
3
4
5
6
C H I N A
DPRK
Paektusan
1
Nanbaotai
Phurunbong
Hwangbong
2
DPRK
Sea of Japan (East Sea)

Quaternary International

We the authors declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.
We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.
We understand that the Corresponding Author is the sole contact for the Editorial process. He/She is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs.

Sincerely,

On behalf of all authors

Yaroslav V. Kuzmin

06 April 2018