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

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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of volcanic glasses and other volcanic rocks in the northern part of the Korean Peninsula, and drawing on our own unpublished data, we suggest that the PNK1 source is most likely located south of Paektusan Volcano. This corroborates the existing evidence for the long-range transport of the material.

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., 2002; 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) (Fig. 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; Yi and Jwa, 2016; Chang and Kim, 2018; Jwa et al., 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) (Fig. 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) (Fig. 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 the caldera rim is generally the higher (Fig. 3) with several peaks, including Sangmujigae (2628 m), Hyangdo (2712 m), Janggun (ca. 2750 m), Haebel (2727 m), Tangyol (2593), Jebi (2593) and Ragwon (2606 m) (Fig. 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 × 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 ignim-brite-forming stage (up to the present). Paektusuan is renowned for the glassy lava flows and sheets, as well as ignimbrite, glass tuffs and pumice. Ignimbrites contain fiamme 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-Mil-lennium 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 volcanioclastics (breciated lava, welded breccia, and tuffaceous breccia). The most representative sections of this formation are observed on Janggun and Hyangdo peaks on the caldera rim (Fig. 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 Fig. 4, A); “rhyolitic obsidian” and “trachydacritic 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 Paektusan 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 (Fig. 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 comendite 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 Fig. 4, A).
This led to establishment of two geochemical groups of volcanic glass, PNK2 and PNK3 (see Table 1 and Fig. 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 pumiceous, 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

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.

<table>
<thead>
<tr>
<th>Element</th>
<th>PNK1 (n = 38)</th>
<th>s.d.</th>
<th>PNK2 (n = 7)</th>
<th>s.d.</th>
<th>PNK3 (n = 3)</th>
<th>s.d.</th>
<th>Chongjin obsidian</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na (%)</td>
<td>3.07 ± 0.09</td>
<td></td>
<td>3.80 ± 0.23</td>
<td></td>
<td>4.17 ± 0.11</td>
<td></td>
<td>3.00</td>
</tr>
<tr>
<td>Al (%)</td>
<td>6.76 ± 0.48</td>
<td></td>
<td>5.78 ± 0.58</td>
<td></td>
<td>8.19 ± 0.25</td>
<td></td>
<td>6.86</td>
</tr>
<tr>
<td>Cl</td>
<td>703 ± 87</td>
<td></td>
<td>1435 ± 671</td>
<td></td>
<td>429 ± 53</td>
<td></td>
<td>706</td>
</tr>
<tr>
<td>K (%)</td>
<td>4.19 ± 0.28</td>
<td></td>
<td>3.89 ± 1.31</td>
<td></td>
<td>4.51 ± 0.59</td>
<td></td>
<td>4.78</td>
</tr>
<tr>
<td>Sc</td>
<td>1.10 ± 0.09</td>
<td></td>
<td>1.31 ± 0.59</td>
<td></td>
<td>4.66 ± 0.67</td>
<td></td>
<td>1.15</td>
</tr>
<tr>
<td>Mn</td>
<td>310 ± 7</td>
<td></td>
<td>864 ± 219</td>
<td></td>
<td>1036 ± 32</td>
<td></td>
<td>308</td>
</tr>
<tr>
<td>Fe (%)</td>
<td>1.08 ± 0.02</td>
<td></td>
<td>2.96 ± 0.1</td>
<td></td>
<td>3.70 ± 0.06</td>
<td></td>
<td>1.04</td>
</tr>
<tr>
<td>Co</td>
<td>0.28 ± 0.07</td>
<td></td>
<td>0.21 ± 0.1</td>
<td></td>
<td>1.17 ± 0.21</td>
<td></td>
<td>0.40</td>
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<tr>
<td>Zn</td>
<td>111 ± 138</td>
<td></td>
<td>245 ± 9</td>
<td></td>
<td>139 ± 19</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>Rb</td>
<td>236 ± 9</td>
<td></td>
<td>302 ± 27</td>
<td></td>
<td>132 ± 5</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Sr</td>
<td>28 ± 6</td>
<td></td>
<td>&lt; 5 ± 2</td>
<td></td>
<td>&lt; 5 ± 2</td>
<td></td>
<td>30</td>
</tr>
<tr>
<td>Zr</td>
<td>251 ± 12</td>
<td></td>
<td>1430 ± 312</td>
<td></td>
<td>506 ± 19</td>
<td></td>
<td>19</td>
</tr>
<tr>
<td>Nb</td>
<td>0.37 ± 0.03</td>
<td></td>
<td>0.32 ± 0.2</td>
<td></td>
<td>0.15 ± 0.01</td>
<td></td>
<td>0.33</td>
</tr>
<tr>
<td>Cs</td>
<td>3.90 ± 0.16</td>
<td></td>
<td>4.36 ± 0.62</td>
<td></td>
<td>1.40 ± 0.03</td>
<td></td>
<td>3.62</td>
</tr>
<tr>
<td>Ba</td>
<td>102 ± 36</td>
<td></td>
<td>50 ± 20</td>
<td></td>
<td>61 ± 17</td>
<td></td>
<td>117</td>
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<tr>
<td>La</td>
<td>68 ± 2</td>
<td></td>
<td>164 ± 6</td>
<td></td>
<td>80 ± 4</td>
<td></td>
<td>64</td>
</tr>
<tr>
<td>Ce</td>
<td>137 ± 4</td>
<td></td>
<td>322 ± 13</td>
<td></td>
<td>155 ± 7</td>
<td></td>
<td>129</td>
</tr>
<tr>
<td>Nd</td>
<td>49 ± 5</td>
<td></td>
<td>125 ± 19</td>
<td></td>
<td>65 ± 2</td>
<td></td>
<td>53</td>
</tr>
<tr>
<td>Sm</td>
<td>10.86 ± 0.5</td>
<td></td>
<td>23.6 ± 9</td>
<td></td>
<td>11.9 ± 0.3</td>
<td></td>
<td>10.4</td>
</tr>
<tr>
<td>Eu</td>
<td>0.27 ± 0.06</td>
<td></td>
<td>0.33 ± 0.03</td>
<td></td>
<td>0.51 ± 0.12</td>
<td></td>
<td>0.33</td>
</tr>
<tr>
<td>Tb</td>
<td>1.62 ± 0.12</td>
<td></td>
<td>3.16 ± 0.44</td>
<td></td>
<td>1.48 ± 0.01</td>
<td></td>
<td>1.44</td>
</tr>
<tr>
<td>Dy</td>
<td>10.3 ± 0.8</td>
<td></td>
<td>19.9 ± 2.3</td>
<td></td>
<td>8.1 ± 0.4</td>
<td></td>
<td>10.3</td>
</tr>
<tr>
<td>Yb</td>
<td>4.55 ± 0.34</td>
<td></td>
<td>9.02 ± 0.78</td>
<td></td>
<td>4.05 ± 0.48</td>
<td></td>
<td>4.12</td>
</tr>
<tr>
<td>Lu</td>
<td>0.72 ± 0.06</td>
<td></td>
<td>1.34 ± 0.18</td>
<td></td>
<td>0.56 ± 0.03</td>
<td></td>
<td>0.57</td>
</tr>
<tr>
<td>Hf</td>
<td>10 ± 0.3</td>
<td></td>
<td>40.3 ± 9</td>
<td></td>
<td>14.6 ± 0.3</td>
<td></td>
<td>9.4</td>
</tr>
<tr>
<td>Ta</td>
<td>6.77 ± 0.42</td>
<td></td>
<td>10.5 ± 2.7</td>
<td></td>
<td>4.28 ± 0.1</td>
<td></td>
<td>6.05</td>
</tr>
<tr>
<td>Th</td>
<td>27.5 ± 0.9</td>
<td></td>
<td>33.8 ± 7.8</td>
<td></td>
<td>5.2 ± 0.5</td>
<td></td>
<td>25.6</td>
</tr>
<tr>
<td>U</td>
<td>7.1 ± 3.0</td>
<td></td>
<td>11.4 ± 3.9</td>
<td></td>
<td>5.2 ± 0.5</td>
<td></td>
<td>8.6</td>
</tr>
</tbody>
</table>

* s.d – standard deviation.
are distributed spatially, calling to mind diversions (Fig. 6, nos. 5–6). This diversity suggests that the "geological" transparent in thick edges, and with small vesicles and mineral inclusions (collection of O.L. Moreva); 4–6 – 'archaeological' obsidians from Primorye Province: 2 – from Aleksee-Nikolskoe 1 site (collection of N.A. Dorofeeva); 5 – from Voelvoda 2 site (collection of N.A. Dorofeeva); and 6 – from Luzanova Sopka 3 site (collection of O.L. Moreva).

Further geochemical characterization of obsidian artifacts has been carried out since the year 2000. Popov et al. (2005) analyzed obsidian flakes from two Upper Palaeolithic 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 Palaeolithic 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 36Ar, 38Ar, and 40Ar 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 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 38Ar as a tracer. Flame spectrophotometry was used to determine K content. The decay constants and 40K 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 \( 40K/\text{K} = 1.167 \times 10^{-4} \) 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 (Fig. 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". Even though we call this sample "Chongjin", we do not insist that it was transported by natural agents (like river) from Paekusan region to Chongjin area. The name "Chongjin" is just a provisional label for localization of this specimen.

Table 2

<table>
<thead>
<tr>
<th>Sample</th>
<th>K, % (±2σ)</th>
<th>Ar(_{\text{int}}), %</th>
<th>Ar(_{\text{rad}}), ng/g (±2σ)</th>
<th>Age, Ma (±2σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chongjin</td>
<td>4.5 ± 0.09</td>
<td>46</td>
<td>0.412 ± 0.014</td>
<td>1.34 ± 0.07</td>
</tr>
<tr>
<td>P-8A*</td>
<td>4.4 ± 0.09</td>
<td>55</td>
<td>0.354 ± 0.011</td>
<td>1.25 ± 0.06</td>
</tr>
<tr>
<td>K-13</td>
<td>5.11 ± 0.06</td>
<td>–</td>
<td>1.873 ± 0.010</td>
<td>5.28 ± 0.14</td>
</tr>
</tbody>
</table>

*Artifact from the Timofeevka 1 site, Primorye Province, Russia (see Kuzmin et al., 2002).
There is a very small chance that the provenance of the Chongjin sample is determined incorrectly, and it did not come from the North Korea; however, the results of recent analyses (see below) overruled it.

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 (Fig. 7B) revealed well-developed hatching, fractures and mineral inclusions in otherwise homogeneous glass. Study under optical microscope (Fig. 7C) revealed a fluidal-striped 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 ca. 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. 1.0–1.49 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 K2O over Na2O 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.

The most probable source for geological obsidians is the area of volcanoes situated some 40–50 km southeast of Paektusan (see Fig. 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 (Nampotaeans) Volcano. This corresponds to the field of trachytes and trachydacites between Hwangbong and Phurunbong volcanoes (Ri, 1993: 331–332) (see Fig. 8). Unfortunately, chemical data for these rocks are not reported.

There was a small chance that source for PNK1 might be associated with the Pliocene to early Pleistocene volcanism of the...
Kilju–Myongchon region (around Hwasong and Myongchon; see Fig. 8, Nos. 4–5), notably the rocks (predominantly alkali rhyolites) of the Chibosan Group (Kim and Pak, 1993). The Hydrogrobong Formation of the Chibosan Group includes rhyolites, perlites or pitchshoves, and obsidians (Kim and Pak, 1993: 324). However, the K–Ar dating of subalkali 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 Chibosan Group (Kim and Pak, 1993: 324). Based on available information, there is no solid evidence to support locating the PNK1 source in the Kilju–Myongchon region.

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 Fig. 1 (Yi and Jwa, 2016: 38), they show locations for several samples to the southeast of Paektusan, some in the Nambatai area, another up to 90 km from Paektusan near the town of Paengam 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 collected from Chongjin, we fully understand that only future fieldwork in the country can complete 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quaint.2018.12.028.

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