

Pleistocene volcanism and the geomorphological record of the Hrazdan Valley, central Armenia: linking landscape dynamics and the Palaeolithic record

J. E. Sherriff^{1*}, K. N. Wilkinson², D. S. Adler³, D. Arakelyan⁴, E. J. Beverly⁵, S.P.E Blockley¹, B. Gasparyan⁶, D. F. Mark⁷, K. Meliksetyan⁴, S. Nahapetyan⁸, K. J. Preece⁹, R.G.O Timms¹

*Corresponding author: jenni.sherriff@rhul.ac.uk

¹Centre for Quaternary Research, Department of Geography, Royal Holloway, University of London, Egham, Surrey, TW20 0EX

²Department of Archaeology, Anthropology and Geography, University of Winchester, Winchester, SO22 4NR, UK.

³Department of Anthropology, Old World Archaeology Program, University of Connecticut, 354 Mansfield Road, Unit 2176, Storrs, CT 06269, USA

⁴Institute of Geological Sciences, National Academy of Sciences of the Republic of Armenia, 24a Marshall Baghramyan Avenue, 0019, Yerevan, Armenia.

⁵Department of Earth and Atmospheric Sciences, University of Houston, 507 Cullen Boulevard, Houston, TX 77204-5007, USA

⁶Institute of Archaeology and Ethnography, National Academy of Sciences of the Republic of Armenia, Charents 15, 375019 Yerevan, Armenia.

⁷NERC Argon Isotope Facility, Scottish Universities Environmental Research Centre, Scottish Enterprise and Technology Park, Rankine Avenue, East Kilbride, G75 0QF, UK.

⁸Department of Cartography and Geomorphology, State University of Yerevan, Alek Manukyan 1, 375049 Yerevan, Armenia.

⁹Department of Geography, College of Science, Swansea University, Singleton Park, Swansea, SA2 8PP, UK

Keywords

Pleistocene, palaeogeography, volcanism, geomorphology, Palaeolithic, Gegham Range, tectonism, ⁴⁰Ar/³⁹Ar chronology, Southern Caucasus

Abstract

The Southern Caucasus lies at the intersection of Africa, the Levant and Eurasia, and is thus a region of considerable interest in the study of Pleistocene hominin population dynamics and behaviour. While Palaeolithic archaeological sites in the region such as Dmanisi and Nor Geghi 1 attest to such palaeogeographic significance, a greater understanding of the chronology and nature of climatic and geomorphic changes in the region is needed to fully understand hominin settlement dynamics. The Hrazdan river valley, central Armenia, has the potential to offer such insights given its rich Palaeolithic record and complex history of Pleistocene infill as a result of alluvial, lacustrine, aeolian, and volcanic processes. We therefore present a stratigraphic framework for basin infill and hominin activity during the Pleistocene, based on extensive geomorphological and geological mapping, published chronometric results (⁴⁰Ar/³⁹Ar and K-Ar), and archaeological survey. We demonstrate that the onset of Pleistocene volcanism in the Gegham Range to the immediate east of the Hrazdan valley occurred around 700 ka BP, after which there were several phases of effusive eruption lasting until 200 ka. Interbedded with lava emplaced by these eruptions are alluvial and lacustrine sequences, some with evidence of pedogenesis and several of which have yielded Palaeolithic artefacts. Taken together these sequences suggest a cyclical model of infill whereby lava flow along the valley resulted in the blockage of the palaeo-Hrazdan river and lake formation in the lee of the lava dams. Breaching of these dams resulted in a shift to predominately fluvial deposition, and the consequent development of floodplain soils. Hominin populations exploited the floodplains at times when the last of

these phases coincided with interglacial and interstadial climates, but they also occupied the surrounding valley sides during the same warm, humid phases.

1. Introduction

Fluvial systems have long been recognised as important archives that link Pleistocene environmental change and the Palaeolithic archaeological record (see Chauhan et al., 2017 for a detailed review). In several geographical regions correlation of geomorphological development with records of human activity and climatic change in such systems has enabled the construction of Palaeolithic occupation chronologies (e.g., Bridgland, 2000; Bridgland et al., 2003; Antoine et al., 2015; Maddy et al., 2015). The Southern Caucasus (the modern-day Republics of Armenia, Azerbaijan, and Georgia) was a land bridge between Africa and Eurasia throughout the Quaternary and is therefore a key region for understanding hominin dispersal and behaviour during the Pleistocene. Several archaeological sites attest to the region's importance; these include Dmanisi, Georgia, where the earliest evidence for *Homo* outside of Africa has been recovered (Gabunia et al., 2000, 2001; Ferring et al., 2011), and Nor Geghi 1, Armenia, which records early evidence for the use of complex stone tool technologies (Adler et al., 2014). Open-air and cave sites documenting Lower, Middle, and Upper Palaeolithic behaviours have been described (e.g., Adler et al., 2006; Liagre et al., 2006; Fernández-Jalvo et al., 2010; Mercier et al., 2010; Ghukasyan et al., 2011; Pinhasi et al., 2011; Adler et al., 2012; Tushabramishvili et al., 2011; Egeland et al., 2014, 2016; Gasparyan and Arimura 2014; Moncel et al., 2015; Glauberman et al., 2016; Pleurdeau et al., 2016; Kandel et al., 2017); however, the chronology and nature of climatic and geomorphological changes in the region require further attention before a better comprehension of the rich archaeological record can be achieved.

The Hrazdan river basin, central Armenia, has the potential to offer such insights given that its fluvial and Palaeolithic archaeological records are associated with volcanism that occurred during several intervals in the Pleistocene (Badalian et al., 2001; Arutyunyan et al., 2007; Lebedev et al., 2011, 2013). Over the last few decades the Hrazdan basin has been intensively studied by geologists, geomorphologists, and archaeologists (e.g. Karapetian, 1987; Karapetian et al., 2001; Adler et al., 2012, 2014; Frahm et al., 20117). These studies have primarily focused on understanding (a) the mode and chronology of volcanism in the mountain ranges either side of the Hrazdan river, and (b) site formation processes and developments of stone tool technologies in Palaeolithic archaeological sites within the Hrazdan basin. From these studies, it is clear that the Hrazdan valley contains an extensive record of volcanic strata with interbedded fluvial and lacustrine sequences. Moreover, the widespread occurrence of such volcanic deposits allows for both the correlation of sequences, but also the development of precise chronologies through by radiometric dating. Therefore this paper presents a stratigraphic framework for the Hrazdan valley, based on the results of geological and geomorphological mapping, archaeological survey and excavation. Through combining these field and desktop data with new and previously published chronometric results, we produce a model for volcanism, geomorphological development and hominin activity in the Hrazdan valley during the Pleistocene.

2. Background

2.1. Geological and geographical setting

Armenia lies on the southern slopes of the Lesser Caucasus (the latter are approximately 2000–4000 m above sea level [asl]), which in turn is located 100–200 km S of the Greater Caucasus range (> 5000 m asl). Both ranges were formed as a result of crustal contraction caused by the collision of the Arabian and Eurasian continental plates from the Miocene onwards. Collision continues at the present day at an estimated rate of $20 \pm 3 \text{ mm yr}^{-1}$ (Reilinger et al., 1997), and in turn drives regional uplift of $0.3\text{--}1.0 \text{ mm yr}^{-1}$ in the eastern Great Caucasus and $0.2\text{--}0.3 \text{ mm yr}^{-1}$ in the Lesser Caucasus (Mitchell and Westaway, 1999). Associated with this

87 tectonism has been the development of major E–W and N–S trending faults (Philip et al., 2001; Karakhanian
88 et al., 2004), and several phases of volcanic activity spanning the Upper Miocene to the Holocene (Borsuk et
89 al., 1989; Arutyunyan et al., 2007). The Hrazdan river is the main drainage of central Armenia and forms the
90 link between two principal basins in the Central Armenian Highlands, Lake Sevan and the Ararat Depression.
91 The former, a large intermontane lake of which the Hrazdan is the sole drainage, is a product of regional
92 tectonic processes. Specifically, the lake has formed as a consequence of strike-slip motion along the Sevan-
93 Pambak fault (Karakhanian et al., 2001). Prior to engineering works from 1937 onwards and which resulted
94 in a lowering of c. 19 m to a present surface elevation of 1896 m asl, lake level was principally controlled by
95 inputs from streams emanating from the Gegham, Vardenis, Sevan and Aregunyats mountain ranges, located
96 SW, S, NE and NW of the lake, respectively. From its outflow at Lake Sevan (40°33'10"N, 44°59'18"S), the
97 Hrazdan river trends in a SW direction towards the village of Karashamb, after which it flows S, through
98 Armenia's capital Yerevan, to meet the River Araxes near the village of Masis in the Ararat Depression
99 (40°0',29"N, 44°,26',27"E; Figure 1). Along its 120 km course, the Hrazdan's elevation drops from 1897 m asl
100 at its outflow to 830 m asl at the confluence with the River Araxes, representing an average decrease of 9 m
101 km⁻¹.

102 The Ararat Depression (also known as the Ararat Basin and Ararat valley) is a subsiding intermontane basin
103 which also formed as a result of regional tectonism, i.e. NW-SE folding and faulting NE of the basin where the
104 South Armenian Microplate (part of the Arabian plate) is subducted beneath the Eurasian plate (Avagyan et
105 al., 2018). Soviet era boreholes recently examined for hydrogeological purposes demonstrate that up to 220
106 m of interbedded fine-grained sediment, sands and gravels, and volcanic deposits outcrop in the basin
107 (Valder et al., 2018), albeit that there is presently only a very limited understanding of the timing and
108 mechanism of basin infill. The Ararat Depression presently contains the River Araxes which flows E from
109 headwaters in northern Anatolia to meet the River Kura (the main axial drainage of eastern Georgia and
110 western Azerbaijan) and which discharges into the Caspian Sea south of Baku (Azerbaijan). While the
111 Quaternary evolution of the Araxes has yet to be studied in any detail, work on the Lower and Middle Kura
112 valley has demonstrated several phases of aggradation and incision in response to Caspian sea level change
113 during the Late Pleistocene and Holocene (Ollivier et al., 2016; von Suchodoletz et al., 2018).

114 Based on its geological setting, it is clear that Pleistocene geomorphological development of the River
115 Hrazdan was controlled by the interplay of (a) water levels in Lake Sevan (which are ultimately controlled by
116 tectonism, but also by temperature and precipitation regimes in the surrounding mountains), (b) subsidence
117 in the Ararat Depression, (c) base level change associated with changing levels of the Caspian Sea, and (d)
118 volcanic activity in the massifs bordering the Hrazdan valley. The Hrazdan valley itself can be split into four
119 broad geological settings along its course (Figure 1): (1) Between its outflow and the confluence with the
120 River Marmarik 19km to the W, it flows through a c. 150 m wide valley cut through Palaeogene marine
121 sedimentary, volcano-sedimentary and volcanogenic formations to the north, and Quaternary volcanic and
122 sedimentary formations to the S (Upper Hrazdan; Sevan-Jrarat reach); (2) between Jrarat and the village of
123 Karashamb 26 km to the SE of Lake Sevan, the valley narrows to a width of around 50 m and passes through
124 Cretaceous – Paleogene marine sedimentary and volcanogenic formations exposed on the NW side of the
125 valley, and Quaternary volcanic strata exposed on the SE side (Upper Hrazdan; Jrarat-Karashamb reach); (3)
126 between Karashamb and Yerevan 19 km to the S, the river has carved a 90m-deep gorge (termed 'Hrazdan
127 Gorge' here and throughout the manuscript) through Quaternary and Pliocene-aged mafic volcanic strata
128 and Miocene marine sands and clays of the Zangian Formation (Nalivkin, 1973); and (4) the 20 km stretch S
129 of Yerevan in which the Hrazdan meets the Ararat Depression and flows as a series of meanders through
130 Quaternary fluvial and lacustrine deposits before its confluence with the River Araxes (Lower Hrazdan;

131 Kharazyan, 2005). The last of these reaches was not investigated as part of the present project and is not
132 discussed further.

133 The area of the Hrazdan valley is presently characterised by a continental climatic regime, with annual
134 precipitation varying from 800 mm at Lake Sevan to 400 mm in Yerevan (Acopian Center for the Environment,
135 2018). Precipitation is derived from evaporation in the eastern Mediterranean and Black Sea and subsequent
136 transport by westerly winds (Joannin et al., 2014). However, the Quaternary climatic history of the Southern
137 Caucasus is currently poorly understood, with evidence based principally on palaeobotanical evidence from
138 Early Pleistocene lacustrine sequences in southern Armenia (Joannin et al., 2010; Ollivier et al., 2010), and
139 the 600 kyr lacustrine record from Lake Van, eastern Turkey (Litt et al., 2014; Stockhecke et al., 2014; Pickarski
140 et al., 2015; Pickarski and Litt, 2017). These records indicate that interglacial and interstadial periods are
141 characterised by Mediterranean-type arboreal vegetation, while non-arboreal taxa indicating cooler and
142 drier conditions typify glacial and stadial periods. There has similarly been limited study of Pleistocene
143 glaciation in the Southern Caucasus, although observations made in southern Armenia (Ollivier et al., 2010)
144 and the Javakheti Plateau, Georgia (Messenger et al., 2013) suggest that local glaciers reached altitudes as low
145 as c. 1450–1500 m asl during glacial periods.

146 2.2. Quaternary volcanism in the Hrazdan Valley

147 The Hrazdan valley lies at the boundary between the two Quaternary volcanic regions of central Armenia:
148 the Aragats volcanic massive to the W, and Gegham volcanic massive to the E. The former comprises several
149 vents including Mt Aragats (4095 masl), c.39 km NW of the Hrazdan valley; Pokr Arteni (1754 masl) and Mets
150 Arteni (2047 masl) 65 km W of the Hrazdan valley, and Mt. Arailer (2576 masl) c. 11 km W of the Hrazdan
151 valley. To the E, the Gegham Range forms a chain of around 100 volcanic centres occupying an area of c. 2800
152 km². Of particular importance for the Middle Pleistocene history of the Hrazdan valley are volcanoes that lie
153 on the western margins of the Gegham Range, i.e. the Gutansar, Alapars and Fantan domes, which
154 collectively form the Gutansar Volcanic Complex (GVC); Hatis; and Menaksar, and three linked vents, Mets
155 Lcharar, E. Lcharar and W. Lcharar in the north-west margins of the valley (Figure 1). These volcanic features
156 have been mapped and sampled by S. Karapetian and colleagues since the 1960s (e.g. Karapetian 1968, 1987;
157 Karapetian et al., 2001; Lebedev et al., 2013), and therefore the nature and distribution of rhyolitic volcanic
158 deposits are known, while a gross chronology for the entire Gegham Range is also in place. Nevertheless,
159 Karapetian et al. (2001) do not differentiate mafic lavas within the Hrazdan valley, categorising all as
160 'Quaternary andesite-basaltic and basaltic lavas'. Chronology of the volcanism has previously been
161 reconstructed through a combination of potassium-argon (K-Ar), argon-argon (⁴⁰Ar/³⁹Ar) and fission track
162 (FT) dating of effusive and intrusive products (Table 1). These dates indicate an eruptive history for the
163 Aragats volcanic province ranging from 2.5 to 0.49 ma (Chernishev et al., 2002, Meliksetian et al., 2014,) and
164 suggest that both the central edifice and andesitic-dacitic flows from Arailer span the interval 1.4 to 1.2 ma
165 (Lebedev et al., 2011). The Gegham Range has a longer eruptive history. The earliest volcanic deposits
166 comprise intermediate and felsic lavas of the Upper Miocene Kaputan Formation (Arutyunyan et al., 2007),
167 which are exposed in the western part of the Hrazdan valley between the villages of Nurnus and Arzni
168 (Karapetian et al., 2001) and thick Vokhchaberd volcanoclastic suite with pyroclastic and lava units of same
169 age exposed in the upstream of Azat river (Baghdasaryan and Ghuaksyan, 1985). Late Pliocene lava, and
170 'pyroclastic basaltic and basaltic andesite' formations have also been described E of Hatis and Yerevan
171 (Lebedev et al., 2013). Finally, multiple K-Ar and FT dates from the Gegham area suggest several eruptive
172 phases spanning the Middle Pleistocene (0.8–0.2 ma BP [Badalian et al., 2001, Arutyunyan et al., 2007,
173 Lebedev et al., 2013]). It is, however, important to note ambiguities associated with some K-Ar and FT dates
174 due to the lack of a) technical detail included in papers published in the early 1990s and 2000s, and b) the
175 precise context and geological material used for dating (Mitchell and Westaway, 1999).

The Hrazdan valley has arguably been the most important locale for the study of the Armenian Palaeolithic (see Gasparyan and Arimura, 2014 for a review). The first Palaeolithic artefacts recognised as such in Armenia were recovered from Arzni in the Hrazdan Gorge in 1933 (Demyokhin, 1956), followed by further prospection for and excavation of Palaeolithic sites in the middle part of the valley between 1944 and 1949. These later works resulted in the discovery of several open air sites in the area (e.g. Panichkina, 1950; Zamyatnin, 1950; Sardaryan, 1954). Surveys conducted in the vicinity of Gutansar in the 1950s led to the discovery of several open-air sites close to or directly on obsidian sources (e.g. Jraber I–X, Fantan I–II, Kyondarasi I–IV, Lyubin, 1961; Lyubin and Balyan, 1961). Further surveys in 1967 and 1968 in the Hrazdan valley led to the discovery of Yerevan and Lusakert group of Middle Palaeolithic cave sites (Martirosyan, 1970). Systematic excavation of Yerevan and Lusakert caves (the latter comprising two caves, Lusakert Cave 1 and Lusakert Cave 2) started in 1967 and continued until 1990 (Yeritsyan, 1975, Yeritsyan and Korobkov, 1979). The final phase of Soviet period investigation of the Palaeolithic of the Hrazdan started in 1983 with survey and excavation of open-air sites situated on the southern slopes of Hatis. The most important discovery was Hatis 1 where 420 handaxes were recorded among a total assemblage of c. 2100 artefacts, in both surface and stratified contexts (Ghazaryan, 1986). Following Armenian independence in 1991, investigation of the Palaeolithic of the Hrazdan valley has continued as a series of collaborations between the Armenian Institute of Archaeology and Ethnography of the National Academy of Sciences and international research groups. As a result, Lusakert Cave 1 was re-excavated by an Armenian-French team in 1999 and 2001 (Fourloubey et al., 2003) and then again by an Armenian-US-UK team in 2008–2011 (Adler et al., 2012), while an Armenian-Russian expedition examined the Nurnus 1 open-air site in the period 2007–2009 (Lyubin et al., 2010). Further Palaeolithic sites were also found as a result of field surveys conducted since 1999 by B. Gasparyan and colleagues, including the Lower Middle Palaeolithic site of Nor Geghi 1, the Middle Palaeolithic sites of Alapars 1 and Jraber 17, and the Upper Palaeolithic site of Solak 1.

Several of these sites merit further attention given their stratigraphical, geomorphological and chronological context. Although there is presently no chronology, Hatis 1, is on typological grounds the oldest of the known sites. It was reinvestigated by the authors in 2016–2017 during which the previous 1986 test pit was expanded leading to the recovery of 200 obsidian artefacts, and including 11 bifaces of various sizes, 1 core on a biface, and 1 large cutting tool recovered (Adler et al., unpublished data), all of which were provenanced by portable x-ray fluorescence to Hatis (c.f. Frahm et al., 2014a). Nevertheless, Nor Geghi 1 is arguably the most significant Palaeolithic site in the Hrazdan valley given its documentation of the local technological transition between the Lower and Middle Palaeolithic c. 400–325 ka (Adler et al., 2014). It was excavated between 2008 and 2016, and comprises scatters of obsidian artefacts (bifaces, Levallois flakes and cores, blades, non-hierarchical cores, and a variety of retouched tools) deposited on a previous Hrazdan floodplain, while the alluvium and palaeosol sequence is interbedded between two mafic lavas that have been dated using the $^{40}\text{Ar}/^{39}\text{Ar}$ technique (see Section 3, Adler et al., 2014). The remaining archaeological sites all post-date the latest phase of lava deposition. Lusakert Cave 1 comprises cave earth strata deposited within a rock shelter formed in the latest Hrazdan lava, but also an alluvial sequence that developed on the exterior. Both sediment suites include dense concentrations of obsidian tools and debitage accompanied by a vertebrate fauna dominated by Asiatic wild ass (*Equus hemionus*). A chronology is provided by published and unpublished ^{14}C and OSL dates which suggest that occupation spanned 60–35 ka (Fourloubey et al., 2003, Adler et al., 2012). Alapars 1 in contrast is an open-air site high on the eastern flanks of the Hrazdan valley and 4 km N of the Gutansar vent. Scatters of Middle Palaeolithic flakes (including Levallois) and retouched tools were found within an early Late Pleistocene low energy alluvial, aeolian, and palaeosol sequence (Malinsky-Buller et al., unpublished data). Finally, excavation of a 2 x 1 m test pit at the stratified open-air

Upper Palaeolithic site of Solak 1 in 2015 resulted in the recovery of a lithic assemblage rich in obsidian bladelets, cores, flakes, and tools derived from numerous sources (Adler et al., unpublished data). Collectively these Palaeolithic archaeological discoveries demonstrate that the Hrazdan was exploited by hominins during multiple time intervals of the Pleistocene, within a variety of topographic zones ranging from the Hrazdan floodplain to the foothills of the Gegham Range..

3. Methodology

In order to better understand the Pleistocene volcanic and sedimentary sequences and Palaeolithic archaeology of the Hrazdan valley, we conducted desktop- and field-based geological and geomorphological mapping, and archaeological survey of a 70 km stretch between the outflow at Lake Sevan and the village of Ptghni, 8 km NE of Yerevan (and including the 'Tsaghkadzor' and 'Buzakhan' tributary valleys; Figure 1). Our work focused initially on understanding the stratigraphic relationships of the lava flows exposed along the valley and the sedimentary sequences in which archaeological remains have been found, and then on chronological and palaeoenvironmental investigation of particularly important sequences.

The first investigative step was a desktop interpretation of landforms, which was undertaken at scales of 1:5,000 to 1:50,000 using a combination of satellite imagery available from the ESRI™ 'World Imagery' service and Google Earth Pro v7.3. These were used in preference to publicly available low-resolution satellite imagery (for example, LANDSAT) as they allowed for better clarity when mapping subtle geomorphic features. Additional features were identified on the basis of topographic properties using relief-shaded (315° and 45° azimuth) and slope gradient-shaded models constructed from a 5 m digital elevation model provided by the Armenian Institute of Geological Sciences. Where possible, landforms were classified on the basis of their morphological properties, as summarised in Table 2.

Preliminary field study was undertaken in 2009, while more detailed and systematic mapping took place in 2015–2017. Mapping was carried out by walk over survey and vehicle inspection, during which landforms and outcrops were plotted onto 1:10,000 topographic maps. Precise positional information at outcrops and sampling localities was recorded using a Leica Zeno dGPS (resulting in sub-metre horizontal and vertical accuracy following post-processing). Geological units at exposure were identified and described using standard geological and sedimentological techniques (Jones et al., 1999; Jerram and Petford, 2011). In the absence of geochemical characterisation, lava flows were assigned broad classifications based on their colour and phenocryst phases (for example, 'mafic', 'intermediate' and 'felsic'). Where this was not possible, for example in areas where deposits could not be reached on foot, or where outcrops were too heavily weathered to identify characteristic compositions, they were classified as 'undifferentiated'. Individual lava flows were correlated along the valley sides using diagnostic structures and elevation wherever possible. In locations where the valley sides were obscured by vegetation, talus and/or buildings, flow positions were interpolated based on position and elevation of dGPS locations. Where individual lava flows were identifiable, they were named on the basis of their geographical and relative stratigraphic position, with 'I' representing the stratigraphically oldest flow in that area (e.g., 'BJN I–IV'). In cases where the identification of individual flows was not possible because of the absence of exposures or the occurrence of flows with locally restricted distributions, lavas were classified as 'flow groups' (e.g., 'Arailer Flow Group 1' ['ARA FG-1']). It is important to note that lava names are purely descriptive, and only interpreted as being derived from a specific volcano/volcanic complex when explicitly stated as such in the text. Also presented in this paper are two $^{40}\text{Ar}/^{39}\text{Ar}$ dates on mafic lava outcropping above a lacustrine and alluvial sequence at a site (Bird Farm 1) 2 km N of Nor Geghi village and which was sampled alongside lavas from the Nor Geghi 1 site in 2009. Analytical methods used to measure $^{40}\text{Ar}/^{39}\text{Ar}$ ratios are reported in Adler et al., (2014, online supplementary material). Archaeological survey was conducted in 2008 and 2009 during which the Hrazdan Gorge between

265 Karashamb and Bjni was examined in a walk- and drive-over survey. The location of artefacts eroding out of
266 sedimentary exposures and recovered from 0.5 x 0.5 m test pits dug in caves cut into the gorge sides was
267 recorded while the archaeological excavations at Nor Geghi 1 and Alapars 1 were conducted on the basis of
268 the survey findings. Results from the desktop and field-based mapping were vectorised using ArcGIS 10.4 and
269 used to construct a geodatabase of identified geological units. Also incorporated into this database were the
270 results of the archaeological survey, and previously published geological and chronological (where the
271 location was known) data.

272 **4. Pleistocene landforms and the stratigraphy of the Hrazdan valley**

273 *4.1. Volcanic deposits*

274 Maps showing the distribution of Pleistocene strata in the Hrazdan valley are presented in Figures 2–7; the
275 GIS database containing a description of these features is available in Supplementary Information 1. As has
276 been described in Section 2.1 the geology and geomorphology of the Hrazdan valley can conveniently be
277 divided into four sections, three of which are reported here.

278 *4.1.1. Upper Hrazdan: Lake Sevan outflow – Jrarat (Marmarik confluence)*

279 The geological and geomorphological features along the northern side of the Sevan–Jrarat reach of the Upper
280 Hrazdan Valley are characterised by step-sided hills formed of Palaeogene andesites, tuffs, limestones and
281 sandstones (Figure 2, Kharazyan, 2005). Quaternary volcanic features are found predominately to the south
282 of the present day river and here lava flows can be divided into three main complexes, representing at least
283 12 individual flows. Their morphological properties are detailed in S1, but all flows are mafic–intermediate,
284 fine grained and vesicular, and in places, heavily weathered. Lavas emanating from the Lcharar Lava Complex
285 (LSC) have the clearest surface expression and comprise eight individual flows (LSC I–VIII), each with
286 undulating-lobate morphology and with clearly visible flow fronts. These flows extend N and NE from the
287 Lcharar Volcanic Centres and terminate S and SW of the Hrazdan river (Figure 2). To the E they overlie the
288 Sevan (SEV) lava complex, which in turn comprises at least three individual flows (SEV I–III), of which SEV-III
289 has the clearest surface expression. The latter flow exhibits a lobate morphology and extends E from the
290 village of Varser, where it terminates at the margin of Lake Sevan. The Jrarat valley Flow Group (JV-FG) lies
291 to the west of the LSC flow complex, where it is found S and E of the Hrazdan river and thereafter extends
292 downstream to outcrop on the present Hrazdan floodplain. JV-FG is characterised by a 'hummocky'
293 morphology, which may represent the undulating flow top morphology of either a single flow or multiple
294 flows.

295 Further volcanic landforms are also identifiable in the Lake Sevan outflow–Jrarat reach. These include a suite
296 of low, elliptical (a-axis 165–175 m, H:W ratio 0.05–0.09) lavadomes with associated exposures of
297 intermediate lava and several scoria cones, including the Mets Lcharar, E. Lcharar and W. Lcharar vents S of
298 the Hrazdan valley, and Ddmashen-1, located on the N flanks of modern Hrazdan floodplain (Figure 2).
299 Pyroclastic fall deposits comprising pumice lapilli were also identified south of the Ddmashen 1 scoria cone
300 and at Zovaber, but there are no observable contacts between the pyroclastic fall, scoria and the lavas, and
301 thus relationships cannot currently be elucidated.

302 South of the Marmarik confluence is a W–E trending valley (termed here the 'Tsaghakadzor valley').
303 Outcropping on the valley sides are several distinct mafic and intermediate lava flows which rest
304 unconformably on Palaeogene granites and diorites (Figure 2). At the base of the valley are several outcrops
305 of pumice lapilli that form two distinct suites. The first is a pyroclastic fall deposit which contains frequent
306 obsidian clasts and is limited to a small area on the S side of the valley. The second comprises ignimbrite

307 deposits (pumice-rich pyroclastic flow deposits which outcrop extensively on the N side of the valley. The
308 truncation of these beds by fluvial processes and subsequent infilling with gravel is notable in several
309 localities.

310 4.1.2. *Upper Hrazdan: Jrarat - Karashamb*

311 The geological and geomorphological features of the Hrazdan valley between Jrarat and Karashamb are
312 shown in Figure 3. In this stretch the Hrazdan river forms the topographic boundary between pre-Quaternary
313 and Quaternary deposits. The pre-Quaternary geologies exposed are predominantly Palaeogene–Cretaceous
314 marine sedimentary (limestones, shales and mudstones), volcanogenic (granites and diorites), and volcano-
315 sedimentary formations (Kharazyan, 2005). These principally outcrop on the N/NW side of the valley, except
316 locally N of the villages of Kaghsi and Solak, where they underlie the Quaternary volcanic deposits. Pre-
317 Cambrian metamorphic and igneous intrusive formations (schists, phyllites, and granites) outcrop on both
318 sides of the river S of Solak village where they underlie Quaternary sedimentary strata (at Solak-16 [Table 3])
319 and lavas.

320 Lava flows outcropping between Jrarat and Karashamb comprise several stratigraphically distinct complexes
321 (Supplementary Information 1). Of these the Kaghsi valley Flow Group (KV-FG) is altitudinally the lowest (and
322 may be a correlative of JV-FG), outcropping in the present valley floodplain between the villages of Kaghsi
323 and Solak (Figure 3). At least two individual flows are clearly identifiable, both comprising dense fine-grained
324 mafic-intermediate lava with large columnar joints, while A'ā (mafic lava with a rough, blocky surface
325 morphology) flowtops are also preserved in several localities. KAG-1 outcrops c.65 m higher than the KV-FG
326 along the valley sides and comprises a single flow of heavily weathered intermediate lava. The flow is
327 bounded to the S by several mafic–intermediate lavas that appear to emanate from the Menaksar Volcanic
328 Centre (MEN-FG). To the W, the Bjni Lava Complex extends 12 km from Solak to Arzakan and includes multiple
329 lava flows outcropping along a c.100 m-high cliff south of the Hrazdan (Figure 3). The complex comprises
330 laterally extensive tabular flows that can be traced along the present valley sides (BJN I–IV). Further lava flow
331 groups (BJN-FG) can be identified within the valley and occur as multiple localised fine-grained mafic-
332 intermediate lavas forming compound braided flow facies. The BJN flows extend 1–2 km S from the valley
333 where they are bounded by the MEN-FG and a suite of flows forming the N extent of the GVC. Associated
334 with the spatially extensive BJN flows are several low, circular–ellipsoidal lava domes (a-axis length = 215–
335 450 m, H:W ratio. 0.07–0.1), while localised felsic lava flows associated with the domes overlie the BJN flows.

336 4.1.3. *Middle Hrazdan (Hrazdan Gorge); Karashamb – Ptghni*

337 Results of the geomorphological survey of the Hrazdan Gorge are presented in Figure 4. Volcanic and
338 sedimentary deposits in the gorge are constrained on their NW side by Palaeogene volcano-sedimentary
339 formations, by lavas emanating from Arailer in the W and SW, and Upper Miocene volcanic deposits (the
340 Kaputan Formation) in the SE (Karapetian et al., 2001; Kharazyan, 2005; Lebedev et al., 2018). Miocene
341 shallow marine deposits outcrop in the southern part of the gorge (between Ptghni and Arzni) and are
342 overlain by Quaternary volcanic deposits (Figures 4 and 5). A total of 18 lava flows and flow groups were
343 mapped along the E and W gorge sides (Figure 6)). These occur as both spatially extensive tabular and
344 localised mafic and mafic-intermediate flows, with frequent and well-developed entablature and colonnade
345 structure (Figure 7). Only three of these lavas have a clear surface expression and the remainder are only
346 exposed in section within the Hrazdan Gorge. Collectively the flows form a plateau on the west side of the
347 gorge which extends from the village of Karashamb southwards towards Getamej. Less continuous lava
348 plateaus are also present on the east side of the gorge between Karashamb and Karenis, and Nurnus and

349 Arzni. The lavas thereafter extend S of Ptghni, the southernmost point of the study area, towards Yerevan
350 and hence into the Ararat Depression (Kharazyan, 2005).

351
352 Lava flows associated with the Arailer Volcanic Centre outcrop on the W side of the gorge at a maximum
353 elevation of 1600 m asl near Karashamb, and extend S down the valley to Ptghni, where they outcrop at 1320
354 m asl (ranging along the reach between 140 and 200 m above present river elevation). Four stratigraphically
355 distinct flow groups are identifiable (ARA-1 to ARA-4), but because there are few clear exposures, individual
356 flows could not be distinguished. The upper most flow group, ARA-4, can be traced E from the Hrazdan valley
357 along a W to E trending valley (termed here the Buzhakan valley) where it caps several mafic-intermediate
358 flows (BUZ-FG). In the SW part of the gorge, the stratigraphically lowest flow group (ARA-1) directly overlies
359 Miocene shallow marine deposits.

360
361 The plateau forming the W side of Hrazdan Gorge and inset against the Arailer lavas, comprises six lava flows
362 of which at least two HGW-VI [i.e. 'Basalt 1' of Adler et al., 2014] and HGW-IV ['Basalt 7' of Adler et al., 2014]
363 are the most spatially extensive and can be traced 15 km SW from Argel. HGW-VI is the youngest lava flow
364 exposed on the W side of the gorge and has the clearest surface expression. Underlying this is HGW-IV, which
365 in the N part of the gorge is underlain by at least three individual flows (HGW-III, HGW-II, HGW-I), two of
366 which (HGW-III and HGW-II) may in part correlate. In the SW part of the gorge, at least five individual lavas
367 (PTG I–V) are identifiable, inset against ARA-1 (Figure 5 and Figure 7). These also overlie Miocene shallow
368 marine deposits in the southern part of the gorge, but a stratigraphic relationship has yet to be established
369 between the PTG and the HGW lavas exposed further north.

370
371 HGW-IV can be traced to the E side of the gorge (it is there named HGE-IV), where it forms part of a suite of
372 six laterally extensive individual flows and flow groups. In the NE part of the gorge, HGE-VII has the clearest
373 surface expression and extends over a 4 km² area north of Karashamb and towards Karenis. To the E, the flow
374 rests against intermediate and mafic lavas mapped by Karapetian et al., (2001) as part of the GVC. HE-VII is
375 underlain by HGE-VI, which in turn outcrops in the base of the gorge between Arzakan and Karenis, while
376 further outcrops of HE-VI are also identifiable in the present-day valley floor of the Hrazdan at the
377 intersection with the Buzhakan valley. HGE-VI overlies HGE-IV, which extends down the E side of the valley
378 to the N of Nurnus. At the latter location, the flows rest on HGE-I, a vertically extensive flow (flow thickness
379 in gorge ranges from 80–160 m) that has been truncated by channel-cutting along the Nurnus valley. The
380 HGE-I flow directly overlies Miocene marine deposits at Arzni and HGE FG-II at Byureghavan. HE-FG-II extends
381 as a single tabular flow S from Byureghavan to Getamej, where a channel feature cut into the gorge reveals
382 at least four separate flows. HE-I and HGE FG-II abut the uppermost PTG flow (PTG-I) which can in turn be
383 traced southwards to Ptghni where it overlies the PTG lava group (PTG II–V).. Between Nurnus and Getamej,
384 HGE-I and HGE-FG II are capped by the stratigraphically youngest flow exposed on the E side of the gorge,
385 HGE-III. The latter flow extends over an area of 8 km² and is constrained on its E extent by lavas forming part
386 of the Kaputan Formation between Nurnus and Arzni (Karapetian, 1968; Karapetian et al, 2001; Lebedev et
387 al, 2018) and 'Doleritic Basalts' as described by Karapetian (1968). A further suite of three individual flows
388 (NUR-I to NUR-III) is also identifiable in the Nurnus valley (Figure 6); the upper most flow (NUR-III) can be
389 found overlying HGE-I on the N side of the Nurnus valley.

390
391 In addition to the mafic intermediate flows described, two extensive (27 km² west of Gutansar and 50 km²
392 centred on Hatis) and two more restricted (3 km² around the Alapars Vent and 1 km² between Gutansar and
393 Hatis) outcrops of obsidian-bearing felsic lava were also recorded E of the Hrazdan Gorge. The distribution of
394 these broadly matches the 'obsidian and perlite lava' previously mapped by Karapetian (1968). North of

395 Gutansar the felsic lavas also occur on the plateau on the W side of the gorge in the Argel area where they
396 both about HGW-VI, but also outcrop above HGW-IV. Pyroclastic fall and flow deposits outcrop in several
397 localities along the W side of the gorge. Most notably several discontinuous but morphologically and
398 stratigraphically comparable sequences of pyroclastic fall deposits comprising interbedded scoria and pumice
399 lapilli and ash are recorded around Karashamb (termed here the 'Karashamb Pyroclastics') in the Hrazdan
400 Gorge, and extending W into the Buzhakan valley, where they are found stratigraphically below the ARA-4
401 Flow Group (Figure 6). Also identifiable in the Buzhakan valley are spatially extensive pyroclastic density
402 current (PDC) deposits, comprising dark-coloured pumice clasts set in an ashy matrix (termed here the
403 'Buzhakan PDC'). These deposits are indurated and in some places welded, include dark-coloured pumice
404 fiamme, and have a clear surface expression along the valley. The Buzhakan PDC can be traced E towards the
405 N flanks of Arailer where it caps a colluvial sequence W of Aramus, and further afield into the Aparan basin
406 to the W of Arailer.

407

408 *4.2. Fluvial landforms*

409

410 Three principal types of fluvial terraces were identified in the Hrazdan valley: (1) accumulations of sands and
411 gravels occurring on the modern floodplain of the Hrazdan river, (2) sands and gravels banked against lavas
412 at the edge of abandoned channels of the Hrazdan, and (3) flat erosional surfaces cut into lava flows and
413 Miocene shallow marine deposits along the valley sides (strath terraces). The first of are the result of late
414 Holocene aggradation and incision of the Hrazdan in its present position, and are not considered further here.
415 A single instance of the second phenomenon was noted butting lava HGW-VI on the outer bend of a cut-off
416 meander at the Lusakert 1 archaeological site and an area to the SW. A 1 m-thick exposure of gravel was
417 noted 11 m above the present stream channel in a bulldozed trench in the latter, while at least 3 m of alluvial
418 sands and silts extending to 10 m above the same stream form part of the Lusakert 1 archaeological site.
419 Strath terraces are infrequent in the Hrazdan Gorge, but are preserved as: (a) a single unpaired terrace at an
420 elevation of 1444 m asl within HGE-VI on the east side of the gorge south of Karashamb, (b) two paired
421 terraces at elevation of 1424 m asl and 1400 m asl on the west side of the gorge cut into the felsic lava
422 outcrop, and on the east side of the gorge within the HGE-IV lava N of Argel, (c) a single unpaired terrace cut
423 into HGW-IV at 1325 m asl S of Nor Geghi, and (d) a single unpaired terrace at 1245 m asl within HGE flow
424 group II W of the village of Getamech.

425

426 *4.3. Sedimentary and archaeological sequences*

427

428 In addition to the features described in Sections 4.1–4.2, multiple sedimentary sequences, several of which
429 have yielded Palaeolithic artefacts, have been found (1) underlying, (2) interbedded-with, and (3) overlying
430 the lava flow sequences in the Hrazdan valley. Summary descriptions of the sequences are presented in Table
431 3 and shown in Figure 8, while the stratigraphic relationships of sequences and volcanic strata are described
432 below.

433

434 The fluvio-lacustrine sequences of Sevan H and Sevan 1 are associated with the SEV-III flow in the vicinity of
435 Lake Sevan. Sevan H, comprised of horizontally bedded ash-rich lake sediments capped by predominately
436 rounded fluvial gravels, directly underlies SEV-III at an elevation of 1931 m asl. Sevan 1 abuts SEV-III at 1934
437 m asl and comprises a c.2 m-thick sequence of massive and horizontally bedded calcareous lacustrine
438 sediments, the latter consisting of predominantly rounded fluvial gravels and sandy shell-rich lake marginal
439 sediments. A survey of the Jrrat-Karashamb reach yielded two sedimentary sequences interbedded
440 between pre-Quaternary bedrock and lava. Bjni 1 comprises a c. 1 m-thick sediment sequence of poorly

sorted angular to sub-angular gravels (colluvium) resting on phyllite (part of the Pre-Cambrian metamorphic basement). The gravels are in turn capped by a medium ash, which is overlain by the BJN-II flow. Solak-16 is a 30m-thick alluvial-palaeosol sequence that also overlies phyllite and which terminates with coarse calibre alluvial fan gravels containing undiagnostic obsidian artefacts (Figure 8). Overlying these sediments are at least three spatially-restricted lava flows, in turn capped by the extensive BJN-I flow and atop which lies the Upper Palaeolithic site of Solak 1. Furthermore, above the volcanic deposits in this area is the Kaghisi 1 sedimentary sequence, which comprises a c. 300m-long, 25m-thick loess-palaeosol sequence with multiple tephra fall units and Middle Palaeolithic artefacts.

In the Hrazdan Gorge, several sequences have been found in association with HGW-VI. These include the fluvio-lacustrine sequence of Bird Farm 1 (Figure 8), which is found directly underlying HGW-VI 800 m W of the present gorge, and the alluvial sequence of Nor Geghi 1 described in Section 2.3. As has been reported elsewhere (Adler et al., 2014), that the northern stratigraphic section at Nor Geghi 1 contains evidence for the local transition from the Lower to the Middle Palaeolithic, with Acheulian bifaces and early hierarchical core technologies, specifically Levallois (Figure 9), bifaces recycled into hierarchical cores, blades, and steeply retouched transverse scrapers found associated in the same stratigraphic units. All the artefacts are made on obsidian, which pXRF measurement mostly attributes to Gutansar sources (domes and pyroclastic flows), but with a secondary component from Hatis, and far transported tertiary elements from Pokr Arteni (70 km W) and Pokr Sevkar (130 km SE). In combination with published data from Africa and Eurasia, the Nor Geghi 1 material is interpreted as additional evidence for the independent, intermittent, and spatially separated evolution of hierarchical core technologies from Acheulian roots rather than the origin and spread of such technologies, and their makers from a single point in Africa.

Sequences interbedded with lavas on the E side of the gorge include Music House, a c. 1m-thick alluvial palaeosol sequence capped by HGE-VIII. Further S, several sedimentary sequences have been recorded in the gorge near Ptghni (Frahm et al., 2017), although as with Music House, Palaeolithic artefacts have yet to be found in section. The Ptghni sequences are comprised of fine-grained alluvial-lacustrine facies representing two phases of sedimentation separated by multiple lava flows. The lowermost sequence (Ptghni A–C, Frahm et al., 2017) overlies mafic lava (PTG-II) and is capped by at least two separate lava flows. The uppermost of these flows, PTG-VI, forms the base of the second sedimentary sequence (Ptghni D–E, Frahm et al., 2017), which is in turn capped by another lava, PTG-IV (Figure 8). Interbedded lavas and lacustrine deposits have also been identified in the Nurnus valley as described in Section 2.3 (here termed ‘Nurnus 1’) (Lyubin et al., 2010), while the site was revisited as part the present survey, and found to directly overlie the uppermost lava flow exposure in the valley, NUR-II. Two further sediment sequences were identified in the vicinity, Nurnus 2, which comprises heavily weathered fine-grained lacustrine deposits lying between lava NUR II and NUR III, and Nurnus 3 which contains fine grained lacustrine deposits with interbedded ash and pumice lapilli found in association with HE-I.

5. A model for Pleistocene development of the Hrazdan valley

The textural and structural properties of the lava flows identified in the Hrazdan valley are indicative of emplacement of principally low viscosity pāhoehoe (lava forming smooth undulating or ropy masses) sheet flows comprised of thick, tabular and laterally continuous facies. Small-scale flows identifiable in several localities represent compound-braided facies likely derived from thin anastomosing pāhoehoe sheet flows. Weathering of the surficial flows along the valley precludes an interpretation of the external flow structure. The exception to this is in the KV-FG, where flow tops consistent with ‘A’ā type lava are clearly preserved. Internal features are well preserved within individual flows, for example, both entablature and columnar

486 jointing are common in the Hrazdan Gorge and Bjni localities, suggesting these are intra-canyon lava flows
487 passing along the pre-existing river valley (Tolan and Beeson, 1984; Lyle, 2000; Reidel et al., 2013; Sheth et
488 al., 2015). The fact that pyroclastic and clastic sediment strata, and mature palaeosols with well-developed
489 Bt horizons are interbedded with the lavas suggest that the flows were not emplaced in rapid succession, but
490 rather that they record multiple phases of effusive volcanism.

491 The suggested stratigraphic association of the lava flows and sedimentary sequences for the Upper-Middle
492 Hrazdan valley is presented in Figure 10. Using the geological and geomorphical evidence presented in
493 Section 4, it is possible to construct a six-phase model of infill of the Hrazdan basin during the Pleistocene.
494 Chronological control for the emplacement of the lava flows in the Upper-Middle Hrazdan comes largely from
495 the $^{40}\text{Ar}/^{39}\text{Ar}$ dating of the mapped flows at Nor Geghi 1 (Adler et al., 2014) and Bird Farm 1 (Table 1). These
496 data demonstrate that HGW-VI was emplaced around 200 ka and HGW-VI/HGE-VI at c. 440 ka. Further
497 chronological control is provided from dating of sedimentary sequences and pyroclastic deposits. An $^{40}\text{Ar}/^{39}\text{Ar}$
498 date obtained on sanidines recovered from cryptotephra in the uppermost floodplain stratum at Nor Geghi
499 1 produced an age of 308 ± 3 ka (Table 1, Adler et al., 2014). In addition, OSL dates from the top of artefact-
500 bearing beds outside of the rockshelter at Lusakert Cave 1 suggest a *terminus ante quem* of c. 36 ka for human
501 activity at this locality (Adler et al., 2012). Additional chronological information is also provided by previous
502 dating of volcanic deposits by K-Ar and FT techniques as reviewed in Section 2.2.

503 5.1. Phase 1 – Volcanic activity in association with the Aragats volcanic area

504 ARA-1 to ARA-4 are the earliest identified lava flows in the Hrazdan valley. They originate in the Arailer
505 volcanic centre and form a spatially extensive suite of deposits on the W side the Hrazdan Gorge. We found
506 no direct association between these flows and the basement geologies and therefore it is presently unclear
507 whether ARA-1–ARA-4 are the earliest Pleistocene deposits in the valley or whether earlier flows have no
508 visible surface outcrop. Chronological control for the Arailer flows comes from a suite of K-Ar dates on lavas
509 at the vent, flanks, and flows proximal to the edifice which span 1.4 to 1.2 ma (Lebedev et al., 2011). Evidence
510 for pyroclastic deposits interbedded between these flows, most notably the ‘Karashamb pyroclastics’,
511 suggest that effusive volcanism was punctuated by periods of explosive volcanic activity. Capping the Arailer
512 flows in the Buzhakan valley is the ‘Buzhakan PDC’ ignimbrite deposit which indicates further explosive
513 activity within the Aragats volcanic centre following Arailer’s final effusive phase. Other PDC deposits
514 generated by explosive eruptions of the Aragats volcano are found throughout the Aragats volcanic massif
515 and beyond (e.g. outcropping below mafic lavas at Aramus on the E side of the Hrazdan valley) and comprise
516 at least six stratigraphically distinct ignimbrites (Gevorgyan et al., 2018). K-Ar age estimates on ignimbrite
517 units to the W and S of Arailer span the period 0.9–0.6 ma (Mitchell and Westaway, 1999; IAEA-TECDOC-
518 1795, 2016. Despite the broad age range of ignimbrite deposition, these deposits collectively act as an
519 important chronostratigraphic marker that divides Lower and Middle Pleistocene strata throughout central
520 Armenia.

521 5.2. Phase 2 – Formation of the Hatis and Gutansar volcanic edifices

522 There is limited evidence for the geomorphological development of the Hrazdan valley in the interval
523 between the cessation of effusive volcanism from Arailer and the K-Ar dates from the Gegham Range that
524 place the formation of the Hatis and Gutansar edifices at c. 700 ka (Karapetian et al., 2001; Lebedev et al.,
525 2013). Associated with this early Gegham eruptive phase were the extrusion of ‘perlites and obsidians’ and
526 ‘rhyolites and dacites’ (Karapetian, 1968, 1972; Karapetian et al., 2001; mapped as felsic and felsic-
527 intermediate deposits in Figure 4), albeit that the previously published mapping suggests that the relevant
528 flows did not extend as far N or W as the present Hrazdan valley.

529 *5.3. Phase 3– Emplacement of the Ptghni lavas*

530 The first Gegham-derived phase of mafic lava emplacement is associated with the PTG lava complex in the S
531 part of the Hrazdan Gorge. These lavas directly overlie Miocene deposits and are thus the earliest flows in
532 the area, but as is outlined in Section 4.3, there is no discernible stratigraphic relationship between the PTG
533 lavas and the spatially extensive flows found in the Hrazdan Gorge further N. Rather, based on the mapping
534 evidence, the PTG flows represent a SW extension of the NE–SW trending flows of ‘Quaternary andesites and
535 basalts’ and ‘basalts of Doleritic structure’ from Gutansar and Hatis mapped by Karapetian (2001). The PTG
536 lavas would have flowed SW from these volcanic centres, thereby crossing the area of the present Hrazdan
537 valley at an oblique angle, and ultimately extending as far south as Yerevan. The Miocene marine deposits
538 and Arailer lavas (ARA-1) outcropping at a higher elevation in the W side of the gorge north of Ptghni may
539 have acted as a topographic barrier, causing the PTG lavas to flow S thereby blocking the palaeo-Hrazdan.
540 The sedimentological evidence from Ptghni indicates the presence of lakes in the area during the intervals
541 between lava emplacement and which were likely formed as a consequence of lava damming. Age estimates
542 from these SE-trending Hatis and Gutansar flows in Yerevan suggest formation at 560–530 ka (Lebedev et al.,
543 2013). Further evidence to suggest that the PTG lavas pre-date c. 500 ka is the absence of Gutansar- and
544 Hatis-derived obsidian in alluvial and lacustrine sediments sandwiched between flows (as is discussed in
545 Section 5.4, pyroclastic deposits and domes on the western side of Gutansar formed after this date
546 [Aruntyan et al., 2007, Lebedev et al., 2013]). Rather, the obsidian in the Ptghni alluvial and lacustrine
547 deposits is from an unknown source that is not found in deposits interbedded with younger lavas in the
548 Hrazdan valley (Frahm et al., 2017).

549 *5.4. Phase 4– Emplacement of the Hrazdan Gorge lavas*

550 The timing of lava emplacement in what is now the Hrazdan Gorge north of Ptghni is based principally on the
551 occurrence of the $^{40}\text{Ar}/^{39}\text{Ar}$ dated spatially extensive HGE-IV/HGW-IV and HGW-VI lava flows. However, in
552 trying to compile a narrative of deposition it is important to note that the correlation of lava flows across the
553 gorge is problematic. Only one flow, HGE-IV/HGW-IV can be confidently mapped in both sides of the gorge
554 and that only because of its association with the GVC felsic deposits that outcrop on the W and E side of the
555 gorge at Argel. However, the elevation difference between HGE-IV/HGW-IV flow exposures on the W and E
556 side of the gorge (a maximum altitudinal difference of 50 m, Figure 11) is instructive and might offer an
557 explanation for the difficulties of cross-gorge lava correlation. These data strongly suggest that a fault runs
558 along the gorge and along which the Hrazdan has down cut, while differential uplift has occurred either side
559 raising lava flows to different levels. This process is in contrast to the upper reaches of the valley, where
560 fluvial incision has principally exploited the geological contact between Quaternary and pre-Quaternary
561 lithologies. Further evidence for deformation, albeit not directly associated with the putative Hrazdan Gorge
562 fault, is the high angled lava flows observed in the Nurnus valley (NUR I and II) and strongly dipping beds in
563 the Nurnus 1 sequence, neither of which correspond to present topography. The presence of a felsic lava
564 dome beneath the Nurnus deposits is interpreted as causing the displacement of the earlier strata during
565 dome emergence, demonstrating that endogenous volcanic activity occurred subsequent to the
566 emplacement of the mafic lavas in the Hrazdan valley.

567 The flows observed in the Hrazdan Gorge likely originate from the Hatis, Gutansar and Menaksar vents,
568 although it should be noted that no individual flow exposed in the gorge has a surface expression that can
569 be traced to any of these edifices. The presence of alluvial sequences interbedded between the lavas
570 indicates that flow was along the course of the palaeo-Hrazdan and in a southerly direction. As HGW-VI is
571 stratigraphically the youngest flow, its 200 ka chronology provides a minimum age for lava emplacement in
572 the Hrazdan Gorge. Therefore, given previous K/Ar ages that suggest volcanic activity in the western Gegham

573 Range began at c. 700 ka (Karapetian et al, 2001; Lebedev et al., 2013), the $^{40}\text{Ar}/^{39}\text{Ar}$ data demonstrate that
574 the Hrazdan Gorge volcanic deposits formed entirely within the Middle Pleistocene. With this in mind, it is
575 possible to build a relative chronology of lava emplacement in the gorge. At least five flows are found below
576 HGW-IV/HGE-IV in the Hrazdan Gorge, and thus they must all predate 440 ka. On the E side of the gorge,
577 HGE-I and HGE-II both have lower contacts on Miocene marine deposits and are thus the earliest flows in this
578 part of the gorge. It is important to note that HGE-I outcrops across a broader range of elevations than the
579 other flows within the gorge, while rather than following the present valley axis, HGE-I may have flowed
580 obliquely across it, forming a topographic high point on the E side around which later lavas flowed. HGE-I
581 cannot be identified at an equivalent position on the W side of the gorge, and thus the palaeo-Hrazdan may
582 have flowed around the solidified HGE-I flow in a broadly similar position to that of the present river. NUR
583 lavas outcrop above HGE-I in the Nurnus valley, while interbedded and capping lacustrine sediments indicate
584 that lake formation occurred in the periods between effusive eruptions, likely due to lava damming of the
585 Hrazdan and/or Nurnus valley.

586 The presence of further lacustrine and alluvial deposits between separate lava flows in the Hrazdan Gorge,
587 for example at both Nor Geghi 1 and Bird Farm 1, suggests that the flows did not occur in rapid succession,
588 but rather after the development of a lacustrine environment and/or the re-establishment of a fluvial system
589 (likely the palaeo-Hrazdan). It is notable in this regard that several phases of pedogenesis are found within
590 floodplain deposits at Nor Geghi 1, for example the occurrence of mature Bt horizons (e.g. Unit 2 of Adler et
591 al., 2014) and multiple palaeosols, indicates landscape stability over a long period of time between intervals
592 of effusive volcanism. Following the emplacement of HGE-IV/HGW-IV at c. 440 ka, there were several further
593 phases of volcanic activity, resulting in the emplacement of HGE-V and HGE-VI, albeit that there is no direct
594 stratigraphic relationship between these flows. Based on current chronological evidence, HGW-VI (c. 200 ka)
595 is the youngest flow and represents the final period of volcanic activity affecting the Hrazdan valley.

596 *5.5. Phase 5 – Emplacement of lavas in the Upper Hrazdan*

597 Several stratigraphically distinct phases of lava emplacement are clear from mapping the Jrarat–Karashamb
598 reach, but the paucity of chronological evidence means that it is difficult to reconstruct the timing of the
599 relevant phases. Two K-Ar ages of 0.54 ± 0.02 ma BP and 0.53 ± 0.03 ma BP are associated with the Menaksar
600 edifice S of the Hrazdan valley (Lebedev et al., 2013), providing a maximum age for the MEN-FG flows
601 emanating from this volcanic centre. It is likely that the lavas forming the BJN lava complex flowed down the
602 palaeo-Hrazdan valley, as the presence of alluvial sequences (Bjni 1 and Solak 16) underlying these lavas
603 indicates that they flowed into a floodplain environment that had formed over the pre-Quaternary bedrock
604 geologies. It is important to note, however, that mafic lava clasts are absent from the gravel-rich alluvial
605 sequences, indicating that the MEN-FG lavas were the first to be emplaced in this part of the valley.
606 Consequently, two hypotheses can be suggested regarding the sequence of events in this part of the valley.
607 First, is that the emplacement of the MEN-FG lavas occurred initially and thereby formed a topographic
608 barrier, funnelling the BJN lavas SW along the Hrazdan valley. Second is that the BJN lavas were emplaced
609 first, followed by a later eruptive episode from Menaksar, producing the volcanic features at 0.5 Ma, and
610 thus capping the BJN flows. Nevertheless, it is important to note that in the NE sector of the Hrazdan Gorge,
611 BJN-I is found in association with HGE-VII, which post-dates 440 Ka, indicating that the BJN flows may have
612 been emplaced during a later eruptive episode than the MEN flows. The presence of the KV-FG outcropping
613 at the base of the Hrazdan valley (Figure 11) may indicate that the KV-FG lavas were emplaced at a later stage
614 following incision of the Hrazdan in its current position; however, the relationship between KV-FG flows and
615 the BJN and MEN lavas is presently uncertain.

616 *5.6. Phase 6 – Emplacement of lavas associated with Lhasar Volcanic Centres*

617 The LSC and SEV lava complexes lie stratigraphically above the valley fill lavas and are thus the youngest flows
618 found in the northern part of the valley. The distribution and surface morphology of the LCS flows indicate
619 that they emanated from the one or more of the three Lcharar volcanic centres (Figure 11) while chronology
620 is provided by a single K-Ar age (Table 1) derived from eastern flank of Mets Lcharar, indicating an age of c.
621 250 ka (Lebedev et al., 2013). The origin of the SEV flows that outcrop to the E of the LCS flows is less clear.
622 The former may represent older flows from the Lcharar volcanic centres, or from volcanic centres elsewhere
623 in the northern sector of the Gegham Range. The SEV flows, however, form an important link between the
624 Hrazdan valley lava/alluvial/lacustrine stratigraphy and the Lake Sevan sedimentary sequence. Indeed, the
625 presence of lake sediments of the latter found in direct association with the stratigraphically oldest flow in
626 the Sevan area (SEV-III) indicates that during the Middle and Late Pleistocene there was a close association
627 between lava emplacement and water levels in Lake Sevan. The SEV lavas may have flowed directly into the
628 lake body, however, the limited exposures in this area and absence of diagnostic sub-aqueous lava facies
629 (e.g., pillow lavas), makes the lake-lava relationship difficult to elucidate.

630 **6. Discussion**

631 *6.1. Mode and chronology of volcanism in the Hrazdan valley*

632 Until now the chronology of volcanism in the western part of the Gegham Range has been based on 31 K-Ar
633 dates on flows and volcanic products around the principal volcanic centres in the area (e.g. Karapetian et al,
634 2001; Lebedev et al., 2013). Using such data, Lebedev et al. (2013) suggest the following phases of volcanic
635 activity: (1) formation of the Hatis and Gutansar edifices with concomitant extrusion of felsic deposits around
636 Hatis at c. 700 ka, (2) a second phase of activity c. 550–500 ka, during which mafic–intermediate lavas flowed
637 from Gutansar and Hatis, as well as the newly formed Menaksar edifice, and (3) a further phase of mafic-
638 intermediate lava flow from Mets Lcharar around 250 ka. However, an alternative chronology is provided by
639 FT dates on obsidians from felsic deposits flanking the west slopes of Gutansar and Hatis, which suggests that
640 these formed between 400 and 200 ka, i.e. several hundred thousand years later than is suggested by the K-
641 Ar dating (Oddone et al., 2000; Badalian et al., 2001).

642 Results from the present geomorphological study and $^{40}\text{Ar}/^{39}\text{Ar}$ dates from the Hrazdan Gorge enables a
643 reassessment of the published chronologies. Rather than a single phase of mafic-intermediate lava eruption
644 from Gutansar, Hatis and Menaksar between 550 and 500 ka and then a second from Lcharar at c. 250 ka,
645 there were in fact many eruptive events spanning the period 550–200 ka. Indeed, morphostratigraphic
646 evidence from the Hrazdan valley reveals the complexity of the volcanic record which varies hugely by type
647 and scale. In the northern part of the Hrazdan valley, for example, there were multiple phases of eruptive
648 activity associated with the Lcharar volcanic centres. Earlier complexes were emplaced around Sevan and
649 Jrarat followed by the later flows of the LCS lava complex. Furthermore, there were at least three eruptive
650 episodes causing lava flows in the Middle Hrazdan valley and which resulted in stratigraphically distinct mafic-
651 intermediate deposits: (1) the emplacement of lavas associated with the Menaksar edifice, likely occurring
652 around 550 ka, (2) the eruption of lavas forming the southern valley side (the BJN lavas), and (3) the later
653 infilling of the Hrazdan valley by the KV-FG lavas following a period of fluvial incision. There were also at least
654 four lava-producing phases that resulted in flows down the Hrazdan valley and which lead to the mafic-
655 intermediate deposits that are now exposed in the Hrazdan Gorge. The presence of lacustrine and alluvial
656 sediments interbedded between these flows in several localities, indicates that eruption was not continuous.
657 Rather, the thickness of the sediment sequences, and the development of mature pedogenic horizons within
658 them indicate that alluvial and lacustrine depositional environments prevailed for the majority of the 550–
659 200 ka time interval.

660 Geological mapping undertaken as part of this study and previously (e.g. Karapetian et al., 2001), has
661 identified pyroclastic deposits outcropping in several localities in the Hrazdan valley. The significance of these
662 is two-fold. First, they can be mapped semi-continuously across the present landscape and thereby provide
663 an important stratigraphic marker. Second, given that the pyroclastic deposits occur within the mafic-
664 intermediate lava sequence, their presence indicates that episodes of explosive eruption occurred as part of
665 a system that was otherwise dominated by effusive volcanic processes. Furthermore, these explosive events
666 produced tephras that were deposited on the Hrazdan river and floodplain, and within lakes, thereby causing
667 their preservation within sedimentary sequences. Such deposits are evident in several outcrops in the
668 Hrazdan valley, notably at Nor Geghi 1, Bird Farm 1, Kaghsi 1 and Nurnus 3, where they offer possibilities for
669 correlation and absolute dating (the latter by $^{40}\text{Ar}/^{39}\text{Ar}$), a potential that has only so far been realised for Nor
670 Geghi 1 (Adler et al., 2014).

671 6.2. *Geomorphical evolution of the Hrazdan valley*

672 As noted in Section 6.1, an important characteristic of the Hrazdan stratigraphic record is the presence of
673 sedimentary sequences interbedded with volcanic deposits, exposures of which can be used to further
674 understand the geomorphological development of the Hrazdan valley during the Pleistocene. Outcrops
675 where sedimentary deposits rest directly on pre-Quaternary bedrock are rare, however, those which have
676 been found (e.g. at Solak and Bjni) indicate alluvial deposition within the valley prior to lava emplacement,
677 in turn indicating that a fluvial system occupied the valley before the onset of Middle Pleistocene volcanism
678 in Gegham. Evidence from Solak 16 suggests a more active fluvial system, as evidenced by multiple channels,
679 and poorly-developed palaeosols (Figure 8D), than that which followed the ingress of Gegham-derived mafic
680 lavas into the valley. The best evidence for landscape development in the intervals between lava
681 emplacement is from the sequences of Nor Geghi 1 and Bird Farm 1, both of which underlie HGW-VI, but also
682 at Ptghni and Nurnus. The lava-lacustrine-alluvial-lava sequences at these sites indicate the following
683 sequence of events (Figure 12): (1) emission of mafic lava from the Gegham Range (it is unclear whether from
684 Gutansar, Hatis or Menaksar), the flow entering the Hrazdan valley, solidifying and damming the river, (2)
685 creation of lakes in the lee of lava dams, (3) readjustment to changing base levels as a consequence of
686 regional tectonism, breaching of the lava dam and a change to predominantly fluvial deposition, (4) stasis,
687 the development of floodplain soils and sub-aerial weathering, and (5) renewed eruption and lava flow
688 starting the cycle again. Phases 2 and 4 are likely to represent by far the highest proportion of time within a
689 single cycle. Based on our current stratigraphic framework, this cycle was repeated at least seven times
690 between the earliest emplacement of lavas in the gorge prior around 550 ka, and the youngest lava
691 emplacement at c. 200 ka. Consequently, although the records are spatially fragmentary, they collectively
692 record a significant proportion of the Middle Pleistocene.

693 Using the $^{40}\text{Ar}/^{39}\text{Ar}$ dates of HGW-VI and the OSL dates from Lusakert Cave 1, it is possible to understand the
694 rate of fluvial incision by the Hrazdan as a result of tectonism that occurred subsequent to the cessation of
695 volcanic activity. Given that the present surface of HGW-VI at Lusakert Cave 1 is at 1437 m asl and the contact
696 between the fluvial terrace on which Middle Palaeolithic occupation took place and the underlying mafic lava
697 is at 1420 masl, there was at least 17 m of down cutting between 200 ka and 36 ka (c. 0.1 mm yr⁻¹).
698 Furthermore, given the elevation difference between the Lusakert Cave 1 terrace and the present channel of
699 the Hrazdan, 42 m of further base level readjustment has occurred since 36 ka (c. 1.7 mm yr⁻¹). The latter
700 rate is considerably less than that observed for the Vorotan river in southern Armenia based on alluvial input
701 into the Aghitu 3 (Layers 10 and 11) archaeological site (3.7 mm yr⁻¹ since 32 ka, [Kandel et al., 2017]), but
702 much higher than the averaged rate of uplift for the region (0.2–0.3 mm yr⁻¹) as proposed by Mitchell and
703 Westaway (1999).

704 Given that the Hrazdan is the sole drainage of Lake Sevan, it is likely that the emplacement of lava dams
705 would have exercised some control on the level of the former lake. Identification of lacustrine sediments in
706 association with lava flows in the Upper Hrazdan enables us to explore these relationships. For example, the
707 presence of lacustrine sediments directly underlying mafic lava at Sevan H and at an elevation of 1931 m asl,
708 indicates that during at least one phase of the Pleistocene, lake level was 15 m or more above the pre-1937
709 level, and therefore that the lake likely extended further west. Furthermore, the presence of lacustrine facies
710 of Holocene age abutting lava at 1934 m asl at Sevan 1, suggest this was likely also the case during at least
711 one phase of the Holocene. It may have been the case that lavas sourced from volcanic centres in the
712 northern part of the Gegham Range flowed into the lake body; this may be evident through the identification
713 of lava textures consistent with sub-aqueous emplacement along the western shore of Lake Sevan.
714 Nevertheless, the relationship of the Hrazdan valley stratigraphy and the Lake Sevan sedimentary record
715 potentially provides a means of linking the Hrazdan archaeological record) with a potentially high resolution
716 and well-discriminated palaeoenvironmental archive.

717 6.3. *Hrazdan valley palaeoenvironments and the Palaeolithic record*

718 K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ dates suggest that the Hrazdan valley volcanic stratigraphy spans at least MIS 13–7 (Figure
719 13), thus representing a time frame of several glacial and interglacial periods for which there are no published
720 palaeoenvironmental and palaeoclimate records from the Southern Caucasus. While the broad vegetation
721 regime of glacial periods is known for the region based on the evidence from Lake Van and Lake Urmia (Litt
722 et al., 2014; Djmalı et al., 2008) the timing and extent of glaciation is not. There are no published
723 geomorphological data to indicate extensive glaciation of the Gegham Range. However, further afield, there
724 are some indications of glacial landforms in the Aragats range (Fabel and Mark, unpublished data), while
725 fluvio-glacial deposits and glacial landforms in the Vorotan valley in the Syunik volcanic massif, southern
726 Armenia, indicate glacial activity in the region during MIS 6 and MIS 12–14 (Olivier et al., 2010). Furthermore,
727 based on data from the Greater Caucasus, Bondarev et al. (1997) estimate that during MIS 2 glaciers
728 developed at elevations 1000–1100 m below those of today, i.e. c. 1900–2500 m asl. Thus, it is likely that
729 mountain glaciers formed either side of the Hrazdan valley in both the Gegham Range and Aragats massive
730 during Middle and Late Pleistocene cold stages, but that subsequent erosion and/or volcanism has obscured
731 the evidence.

732 In addition to the Middle Pleistocene and later record from Lake Van, there are also palaeoenvironmental
733 data of Early Pleistocene age from lacustrine sequences in the Sisian Basin of southern Armenia. Although
734 arguably a poor analogue for the Middle Pleistocene, the palaeoenvironmental proxies from the Sisian
735 deposits also suggest an alternation of dry steppic and humid forested phases during glacials and interglacials
736 respectively (Joannin et al., 2010). Palaeobotanical data from the interglacial phases suggest that rainfall was
737 twice that of today and that mean annual temperature was 4°C higher (Bruch and Gabrelyan, 2002). Indeed,
738 vertebrate and palynological data from the few Southern Caucasus cave strata that contain Palaeolithic
739 artefacts and which predate 200 ka (e.g. Jruchula, Kudaro and Tsona) suggest that hominin activity took place
740 in ubiquitously warm, humid and forested interglacial environments (Vekua and Lordkipanidze 1998, Mercier
741 et al., 2011). Given these sites' location in the Black Sea (Rioni) Basin and consequent association with humid
742 climates, it is even more likely that the relatively arid Hrazdan Basin would have been occupied primarily
743 during warm and humid phases, which indeed is what the limited data suggest. For example, the upper
744 artefact-bearing layers of Nor Geghi 1 are associated with a stable floodplain environment attributed to the
745 peak warmth of MIS 9 (MIS 9e). The lack of pollen preservation means that it is unclear what vegetation was
746 associated with Middle Pleistocene hominin occupation of Nor Geghi 1, but the mature, rubified Bt horizons
747 of the palaeosols in this sequence suggest the development of climax vegetation communities.

748 Vertebrate evidence associated with Late Pleistocene and later Middle Palaeolithic (c. 130–40 ka) sites in
749 both the Black Sea (western and northern Georgia) and Caspian (eastern Georgia and Armenia) basins also
750 suggests that hominins were present in the region primarily during interglacials and interstadials (Adler et
751 al., 2006; Pinhasi et al., 2008). However, possibly in contrast to the earlier period, open environments also
752 seem to have been exploited during the later stages of the Pleistocene, in turn suggesting that vegetation
753 per se was not an overarching constraint. Thus, both open mountain pasture and valley grassland was used
754 for hunting during MIS 5 and MIS 3 interstadials as attested by Palaeolithic sites with vertebrate fossil
755 preservation such as Hovk 1, Kalavan 2 and Lusakert Cave 1 (Ghukasyan et al., 2011, Pinhasi et al., 2011, Adler
756 et al., 2012). Albeit lacking faunal preservation, Alapars 1 is associated with palaeosol development in aeolian
757 and alluvial sediments, suggesting hominin activity in the Gegham foothills during the Late Pleistocene
758 (Malinsky-Buller et al., unpublished data). The position of Middle Palaeolithic sequences of Alapars 1 and
759 Kaghsi 1 (although currently undated) is significant as they are associated with occupation at high altitude
760 (1541 m and 1872 m asl, respectively), areas that would have been subject to severe periglacial conditions
761 during Middle and Late Pleistocene cold stages.

762 A feature of all Palaeolithic sites identified in the Hrazdan valley, is that artefacts assemblages are produced
763 almost entirely on obsidian, which geochemical data suggest was overwhelmingly sourced (>90% in each
764 case) from the flows W and S of Gutansar and Hatis (Adler et al., 2012, 2014; Frahm et al., 2014a, 2014b,
765 2016; Figure 13). Furthermore, as discussed in Section 6.1, the K-Ar chronology for the main phase of obsidian
766 extrusion is c. 480 ka, thereby suggesting that the presence of late Lower and Middle Palaeolithic sites is no
767 coincidence. Both Nor Geghi 1 and Lusakert Cave 1 combined the advantages of a floodplain setting (e.g.
768 access to water, the concentration of medium to large mammals) and proximity to primary and secondary
769 obsidian sources, while the same might also have been true of Alapars 1 (Malinsky-Buller et al., unpublished
770 data). Thus, it is likely that the availability of this high-quality raw material in the Hrazdan basin coupled with
771 the rich floral and faunal resources common to Middle Pleistocene humid interglacials, favoured hominin
772 occupation, and may have helped set the stage for the technological evolution documented at Nor Geghi 1
773 (Adler et al., 2014).

774 7. Conclusions

- 775 • The Hrazdan valley offers a unique archive for understanding volcanism, landscape development,
776 and Palaeolithic occupation during the Middle and Late Pleistocene. Through detailed geomorphical
777 and geological mapping, archaeological survey and preliminary chronological work, we have
778 demonstrated that in contrast to previous evidence, there were at least six phases of effusive
779 volcanism in the western Gegham Range during the Middle and Late Pleistocene. Each phase
780 comprised several intervals of volcanic activity resulting in the emplacement of mafic–intermediate
781 lavas and associated pyroclastic deposits within the Hrazdan valley. Sedimentary sequences
782 interbedded with these lavas indicate a clear pattern of landscape development subsequent to lava
783 emplacement, i.e. lake formation, fluvial activity, and land surface stability. Although spatially
784 fragmentary, collectively these depositional environments operated for the majority of the Middle
785 Pleistocene.
- 786 • Landscape changes in the Hrazdan valley between 550 and 200 ka (i.e. MIS 13–7) were caused by a
787 combination of volcanic activity, hydrological development and climate change. These developments
788 created opportunities for Middle Pleistocene hominins at a time of significant biological, social, and
789 technological evolution. The preservation and discovery of stratified Palaeolithic archaeological sites
790 in the Hrazdan valley indicates that hominins were exploiting floodplain and lake environments
791 primarily during interglacial and interstadial periods.

- The close association of the archaeological sequences and volcanic products from the Gegham and Aragats volcanic massifs provides a rare opportunity for dating Lower and Middle Palaeolithic occupations with a high level of precision through radiometric techniques. Furthermore, the association of the Hrazdan valley stratigraphy with the Lake Sevan lacustrine record means that the Palaeolithic record can be linked to a potentially high resolution palaeoenvironmental archive.
- Future work will focus on developing a robust chronology for the evolution of the Hrazdan valley through systematic $^{40}\text{Ar}/^{39}\text{Ar}$ dating of lava flows and the tephrostratigraphic correlation of sedimentary sequences, and the acquisition of a detailed regional palaeoenvironmental record through the drilling of Lake Sevan. By doing this, we hope to realise the potential of the Hrazdan valley for understanding the behavioural evolution of Middle Pleistocene hominins in the Southern Caucasus and the Armenian Highlands.

8. Acknowledgments

Most of the research reported here was carried out as part of the Leverhulme Trust-funded Palaeolithic Archaeology, Geochronology and Environments of the Southern Caucasus (PAGES) project (RPG-2016-102). Additional funding was provided by the Armenian branch of the Gfoeller Renaissance Foundation (USA), the University of Connecticut (Norian Armenian Studies Program), the L.S.B. Leakey Foundation and the University of Winchester, while the $^{40}\text{Ar}/^{39}\text{Ar}$ dates from Nor Geghi 1 and Bird Farm were funded by an Isotope Geoscience Support grant (IP-1186-0510) awarded by the UK Natural Science Research Council. The authors would like to thank the following individuals for their help in the field and laboratory: Suren Kesejyan (Gfoeller Renaissance Foundation), Ellery Frahm (Yale University), Monika Knul (University of Winchester) and Christina Manning (Royal Holloway, University of London). Finally, we thank Pavel Avesetyan, Director of the Institute of Archaeology and Ethnography, RAS Armenia, for his consistent support of our archaeological work and Karen Bayramyan, Head of the Protection of Monuments of History and Culture Agency for the Kotayk and Gegharkunik Provinces, the Ministry of Culture, Republic of Armenia for his help in securing access to key sites.

9. References

- Acopian Center for the Environment, 2018. Vector Database Armenia. American University of Armenia. <http://www.acopiancenter.am/GISPortal/> (Accessed 07/12/2018).
- Adler, D.S., Bar-Oz, G., Belfer-Cohen, A., Bar-Yosef, O., 2006. Ahead of the game - Middle and Upper Palaeolithic hunting behaviors in the southern Caucasus. *Current Anthropology*, 47, pp. 89–118.
- Adler, D.S., Wilkinson, K.N., Blockley, S., Mark, D.F., Pinhasi, R., Schmidt-Magee, B.A., Nahapetyan, S., Mallol, C., Berna, F., Glauberman, P.J., Raczynski-Henk, Y., 2014. Early Levallois technology and the Lower to Middle Paleolithic transition in the Southern Caucasus. *Science*, 345 (6204), pp. 1609–1613.
- Adler, D.S., Yeritsyan, B. Wilkinson, K.N., Pinhasi, R., Bar-Oz, G., Nahapetyan, S., Bailey, R., Schmidt, B.A. Glauberman, P., Wales, N., Gasparian, B. 2012. The Hrazdan Gorge Palaeolithic Project, 2008–2009. In Avetisyan, P. and Bobokhyan, A. (eds.) *Archaeology of Armenia in Regional Context*, Proceedings of the International Conference dedicated to the 50th Anniversary of the Institute of Archaeology and Ethnography held on September 15-17, 2009 in Yerevan, Armenia. NAS RA Gitutyn Publishing house, Yerevan, pp. 21–37.

831 Antoine, P., Moncel, M.H., Loch, J.L., Limondin-Lozouet, N., Auguste, P., Stoetzel, E., Dabkowski, J., Voinchet,
832 P., Bahain, J.J., Falgueres, C., 2015. Dating the earliest human occupation of Western Europe: new evidence
833 from the fluvial terrace system of the Somme basin (Northern France). *Quaternary International*, 370, pp.
834 77–99.

835 Arutyunyan, E.V., Lebedev, A.V., Chernyshev, I.V., Sagatelyan, A.K., 2007. Geochronology of Neogene–
836 Quaternary volcanism of the Geghama Highland (Lesser Caucasus, Armenia). *Doklady Earth Sciences* 416, pp.
837 1042–1046.

838 Avagyan, A., Sosson, M., Sahakyan, L., Sheremet, Y., Vardanyan, S., Martirosyan, M. and Muller, C., 2018.
839 Tectonic Evolution of the Northern Margin of the Cenozoic Ararat Basin, Lesser Caucasus, Armenia. *Journal*
840 *of Petroleum Geology*, 41(4), pp. 495-511.

841 Badalian, R., Bigazzi, G., Cauvin, M.C., Chataigner, C., Jrbashyan, R., Karapetyan, S.G., Oddone, M., Poidevin,
842 J.L., 2001. An international research project on Armenian archaeological sites: fission-track dating of
843 obsidians. *Radiation Measurements*, 34 (1–6), pp. 373–378.

844 Baghdasaryan, G.P. and Ghukasyan, R.K., 1985. Geochronology of magmatic, metamorphic and ore
845 formations of Armenian SSR. Yerevan, Armenia: Academy of Sciences of Armenian Soviet Socialist Republic
846 (in Russian)

847 Bondarev, L.G., Gobedzhishvili, R.G., Solomina, O.N., 1997. Fluctuations of local glaciers in the southern
848 ranges of the former USSR: 18,000–8000 BP. *Quaternary International*, 38, pp. 103–108.

849 Borsuk, A.M., Ivanenko, V.V., Karpenko, M.I., Chernyshev, I.V., 1989. Precision K-Ar dating of neogenic
850 intrusives of the Trans-Caucasian transversal zone and possible geodynamic effects. *Doklady Akademii Nauk*
851 *SSSR*, 308(5), pp. 1188 - 1191.

852 Bridgland, D.R., 2000. River terrace systems in north-west Europe: an archive of environmental change, uplift
853 and early human occupation. *Quaternary Science Reviews*, 19 (13), pp. 1293 - 1303.

854 Bridgland, D.R., Philip, G., Westaway, R. and White, M., 2003. A long Quaternary terrace sequence in the
855 Orontes River valley, Syria: a record of uplift and of human occupation. *Current Science*, 84 (8), pp. 1080 -
856 1089.

857 Bruch, A.A., Gabrielyan, I.G., 2002. Quantitative data of the Neogene climatic development in Armenia and
858 Nakhichevan. *Acta Universitatis Carolinae e Geologica* 46 (4), pp. 41 - 48.

859 Chauhan, P.R., Bridgland, D.R., Moncel, M.H., Antoine, P., Bahain, J.J., Briant, R., Cunha, P.P., Despriée, J.,
860 LimondinLozouet, N., Loch, J.L., Martins, A.A., 2017. Fluvial deposits as an archive of early human activity:
861 progress during the 20 years of the Fluvial Archives Group. *Quaternary Science Reviews*, 166, pp. 114–149.

862 Chernyshev, I.V., Lebedev, V.A., Arakelyants, M.M., Dzhrbashyan, R.T. and Gukasyan, Y.G., 2002. Quaternary
863 geochronology of Aragats volcanic center (Armenia) by K-Ar isotope dating. *Doklady Akademii Nauk-*
864 *Rossiyskaya Akademiya Nauk*, 384 (1), pp. 95–102.

865 de Silva, S., Lindsay, J.M., 2015. Primary volcanic landforms. *Encyclopedia of Volcanoes*. Academic Press, San
866 Diego, pp. 273–297.

867 Demoyokhin, A.P. 1956. On the discovery of Palaeolithic type obsidian tools in Armenia. In Dolukhanova, N.I.
868 and Yegoyan, V.I. (Eds.) Questions of geology and hydrogeology of the Armenian SSR. Armenian SSR Academy
869 of Sciences Press, Yerevan, pp. 1113 (In Russian).

870 Egeland, C. P., Gasparian, B., Fadem, C.M., Nahapetyan, S., Arakelyan, D., Nicholson C.M., 2016. Bagratashen
871 1, a stratified open-air Middle Paleolithic site in the Debed river valley of northeastern Armenia: A preliminary
872 report. *Archaeological Research in Asia*, 8, pp. 120.

873 Egeland, C.P., Gasparian, B., Arakelyan, D., Nicholson, C.M., Petrosyan, A., Ghukasyan, R., Byerly, R., 2014.
874 Reconnaissance survey for Palaeolithic sites in the Debed River Valley, northern Armenia. *Journal of Field*
875 *Archaeology*, 39(4), pp.370–386.

876 Fernández-Jalvo, Y., King, T., Andrews, P., Yepiskoposyan, L., Moloney, N., Murray, J., Domínguez-Alonso, P.,
877 Asryan, L., Ditchfield, P., Van der Made, J., Torres, T., 2010. The Azokh cave complex: Middle Pleistocene to
878 Holocene human occupation in the Caucasus. *Journal of Human Evolution*, 58(1), pp.103–109.

879 Ferring, R., Oms, O., Agusti, j., Berna, F., Nioradze, M., Shelia, T., Tappen, M., Vekua, A., Zhvania, D.,
880 Lordkipanidze, D., 2011. Earliest human occupations at Dmanisi (Georgian Caucasus) dated to 1.85–1.78 Ma.
881 *Proceedings of the National Academy of Sciences*, 108, pp. 10432–10436.

882 Fink, J.H., Anderson, S.W., 2000. Lava domes and coulees. *Encyclopaedia of Volcanoes*. Academic Press, San
883 Diego, pp.307–319.

884 Fisher, R.V., Schmincke, H.U., 1984. *Pyroclastic Rocks*. Springer Science & Business Media, Berlin, Germany.

885 Folch, A., 2012. A review of tephra transport and dispersal models: evolution, current status, and future
886 perspectives. *Journal of Volcanology and Geothermal Research*, 235, pp.96–115.

887 Fourloubey, C., Beauval, D., Colonge, D., Liagre, J., Ollivier, V., Chataigner, C., 2003. Le paléolithique en
888 Arménie: état de connaissances acquises et données récentes. *Paléorient*, 29, pp. 5–18.

889 Frahm, E., Feinberg, J.M., Schmidt-Magee, B.A., Wilkinson, K.N., Gasparyan, B., Yeritsyan, B., Karapetian, S.,
890 Meliksetian, K., Muth, M.J., Adler, D.S., 2014b. Sourcing geochemically identical obsidian: multiscalar
891 magnetic variations in the Gutansar volcanic complex and implications for Palaeolithic research in Armenia.
892 *Journal of Archaeological Science*, 47, pp. 164–178.

893 Frahm, E., Schmidt-Magee, B., Gasparyan, B., Yeritsyan, B., Karapetian, S., Meliksetian, K., Adler, D.S., 2014a.
894 Ten seconds in the field: rapid Armenian obsidian sourcing with portable XRF to inform excavations and
895 surveys. *Journal of Archaeological Science* 41, pp. 333–348.

896 Frahm, E., Feinberg, J.M., Schmidt-Magee, B.A., Wilkinson, K.N., Gasparyan, B., Yeritsyan, B., Adler, D.S.,
897 2016. Middle Palaeolithic toolstone procurement behaviors at Lusakert Cave 1, Hrazdan Valley,
898 Armenia. *Journal of Human Evolution*, 91, pp.73–92.

899 Frahm, E., Sherriff, J., Wilkinson, K.N., Beverly, E.J., Adler, D.S., Gasparyan, B., 2017. Ptghni: A new obsidian
900 source in the Hrazdan river basin, Armenia. *Journal of Archaeological Science: Reports*, 14, pp.55–64.

901 Gabunia, L., Antón, S., Lordkipanidze, D., Vekua, A., Justus, A., Swisher, C., 2001. Dmanisi and dispersal.
902 *Evolutionary Anthropology*, 10, pp. 158–170.

903 Gabunia, L., Vekua, A., Lordkipanidze, D., Swisher, C.C., Ferring, R., Justus, A., Nioradze, M., Tvalchrelidze, M.,
 904 Antón, S.C., Bosinski, G., Jöris, O., de Lumley, M.-A., Majsuradze, G., Mouskhelishvili, A., 2000. Earliest
 905 Pleistocene hominid cranial remains from Dmanisi, Republic of Georgia: taxonomy, geological setting and
 906 age. *Science*, 288, pp. 1019–1025.

907 Gasparyan, B., Arimura, M., (Eds.) 2014. *Stone Age of Armenia: Guide-Book to the Stone Age Archaeology in*
 908 *the Republic of Armenia*. Center for Cultural Resource Studies, Kanazawa University: Kanazawa.

909 Gevorgyan, H., Repstock, A., Schulz, B., Meliksetian, K., Breitzkreuz, C., Israyelyan, A., 2018. Decoding a post-
 910 collisional multistage magma system: The Quaternary ignimbrites of Aragats stratovolcano, western
 911 Armenia. *Lithos*, 318, pp.267–282.

912 Ghazaryan, H.P., 1986. Upper Acheulian open air site Hatis-1. In Shokiov, V.P. (Ed.) *Archaeological Discoveries*
 913 *for the Year 1984*. Nauka Publishing House, Moscow, pp. 433–434 (In Russian).

914 Ghukasyan, R., Colonge, D., Nahapetyan, S., Ollivier, V., Gasparyan, B., Monchot, H., Chataigner, C., 2011.
 915 Kalavan-2 (north of Lake Sevan, Armenia): A new Late Middle Palaeolithic site in the Lesser Caucasus.
 916 *Archaeology, Ethnology and Anthropology of Eurasia*, 38(4), pp. 39–51.

917 Glauberman, P.J., Gasparyan, B., Wilkinson, K.N., Frahm, E., Raczynski-Henk, Y., Haydosyan, H., Arakelyan, D.,
 918 Karapetyan, S., Nahapetyan, S., Adler, D.S., 2016. Introducing Barozh 12: A Middle Palaeolithic Open-Air Site
 919 on the Edge of the Ararat Depression, Armenia. *ARAMAZD, Armenian Journal of Near Eastern Studies* IX(2)-
 920 2015, pp. 7–20.

921 Harris, E.C., 1979. *The Laws of Archaeological Stratigraphy*. Routledge and Kegan Paul, London.

922 Harris, A.J. and Rowland, S.K., 2015. Lava flows and rheology. *Encyclopaedia of Volcanoes*. Academic Press,
 923 San Diego, pp. 321–342.

924 IAEA-TECDOC-1795, Aspinall, W.P., Charbonnier, S., Connor, C.B., Connor, L.J.C., Costa, A., Courtland, L.M.,
 925 Delgado Granados, H., Hibino, K., Hill, B.E., Komorowski, J.C., McNutt, S., Meliksetian, K., Nakada, S., Newhall,
 926 C., Samaddar, S.K., Savov, I.P., Self, S., Uchiyama, Y., Wilson, T., Yamamoto, T., 2016. *Volcanic Hazard*
 927 *Assessment for Nuclear Installations: Methods and Examples in Site Evaluation*, International Atomic Energy
 928 Agency, Vienna, Austria.

929 Jerram, D.A. and Petford, N., 2011. *The Field Description of Igneous Rocks*. Second Edition, John Wiley & Sons,
 930 Chichester, UK

931 Jerram, D.A. 2002. Volcanology and facies architecture of flood basalts. *Volcanic Rifted Margins*, 362, p.119.

932 Joannin, S., Ali, A.A., Ollivier, V., Roiron, P., Peyron, O., Chevaux, S., Nahapetyan, S., Tozalakyan, P.,
 933 Karakhanyan, A., Chataigner, C., 2014. Vegetation, fire and climate history of the Lesser Caucasus: a new
 934 Holocene record from Zarishat fen (Armenia). *Journal of Quaternary Science*, 29(1), pp.70–82.

935 Joannin, S., Cornée, J.J., Münch, P., Fornari, M., Vasiliev, I., Krijgsman, W., Nahapetyan, S., Gabrielyan, I.,
 936 Ollivier, V., Roiron, P., Chataigner, C., 2010. Early Pleistocene climate cycles in continental deposits of the
 937 Lesser Caucasus of Armenia inferred from palynology, magnetostratigraphy, and ⁴⁰Ar/³⁹Ar dating. *Earth and*
 938 *Planetary Science Letters*, 291(1–4), pp.149–158.

939 Jones, A.P., Tucker, M.E., Hart, J., (Eds.) 1999. *The description & analysis of quaternary stratigraphic field*
 940 *sections*, vol. 7, London, UK. Quaternary Research Association Technical Guide, 7, 295 pp.,

941 Kandel, A.W., Gasparyan, B., Allué, E., Bigga, G., Bruch, A.A., Cullen, V.L., Frahm, E., Ghukasyan, R., Gruwier,
942 B., Jabbour, F., Miller, C.E., 2017. The earliest evidence for Upper Paleolithic occupation in the Armenian
943 Highlands at Aghitu-3 Cave. *Journal of Human Evolution*, 110, pp.37–68.

944 Karakhanian, A., Tozalakyan, P., Grillot, J.C., Philip, H., Melkonyan, D., Paronyan, P., Arakelyan, S., 2001.
945 Tectonic impact on the Lake Sevan environment (Armenia). *Environmental Geology*, 40(3), pp.279–288.

946 Karakhanian, A.S., Trifonov, V.G., Philip, H., Avagyan, A., Hessami, K., Jamali, F., Bayraktutan, M.S.,
947 Bagdassarian, H., Arakelian, S., Davtian, V., Adilkhanyan, A., 2004. Active faulting and natural hazards in
948 Armenia, eastern Turkey and northwestern Iran. *Tectonophysics*, 380(3-4), pp.189219.

949 Karapetian, S.G., 1968. About the age and stratigraphic position of recent rhyolite and rhyodacitic rocks of
950 the Armenian SSR. *Academy of Sciences of Armenian SSR, Earth Sciences*. XXI (N1–2), 60–71 (in Russian).

951 Karapetian, S.G., 1987. Late-orogenic rhyolitic volcanism on the territory of the Armenian SSR and
952 surrounding areas. *Archives of the Institute of Geological Sciences, Armenian SSR Academy of Sciences*,
953 Yerevan, 302 pp (in Russian).

954 Karapetian, S.G., Jrbashian, R.T., Mnatsakanian, A.Kh. 2001. Late collision rhyolitic volcanism in the north-
955 eastern part of the Armenian Highland. *J. Volcanology and Geotherm. Res.* 112, pp. 189–220.

956 Kharazyan H. 2005. Geological map of Republic of Armenia. In: Kharazyan, H, editor. Ministry of nature
957 protection of Republic of Armenia [Internet]. Ministry of Nature Protection of Republic of Armenia, Yerevan.

958 Lebedev, V.A., Chernyshev, I.V., Yakushev, A.I. 2011 The initiation time and the duration of Quaternary
959 magmatism in the Aragats neovolcanic area, Lesser Caucasus, Armenia, *Doklady Earth Sciences*, 437, pp. 808–
960 812.

961 Lebedev, V.A., Chernyshev, I.V., Sagatelyan, A.K., Goltsman, Y.V., Oleinikova, T.I., 2018. Miocene–Pliocene
962 Volcanism of Central Armenia: Geochronology and the Role of AFC Processes in Magma Petrogenesis. *Journal*
963 *of Volcanology and Seismology*, 12(5), pp.310–331.

964 Lebedev, V.A., Chernyshev, I.V., Shatagin, K.N., Bubnov, S.N., Yakushev A.I. 2013. The Quaternary volcanic
965 rocks of the Geghama Highland, Lesser Caucasus, Armenia: geochronology, isotopic Sr–Nd characteristics,
966 and origin. *Journal of Volcanology and Seismology*, 7, pp. 204–229.

967 Liagre J., Gasparyan, B., Olivier, V., Nahapetyan, S., 2006. Angeghakot-1 and the Identification of the
968 Mousterian Cultural Facies of “Yerevan Points” Type in the Southern Caucasus. *Paléorient*32, 5–18.

969 Litt, T., Pickarski, N., Heumann, G., Stockhecke, M., Tzedakis, P.C., 2014. A 600,000 year long continental
970 pollen record from Lake Van, eastern Anatolia (Turkey). *Quaternary Science Reviews*, 104, pp.30–41.

971 Lockwood, J.P., Lipman, P.W., 1980. Recovery of datable charcoal beneath young lavas: lessons from
972 Hawaii. *Bulletin Volcanologique*, 43(3), pp.609–615.

973 Lyle, P., 2000. The eruption environment of multi-tiered columnar basalt lava flows. *Journal of the Geological*
974 *Society*, 157(4), pp.715–722.

975 Lyubin, V.P., 1961 The Upper Acheulian workshop of Jraber. *Abstracts of Reports and Field Investigations of*
976 *the Institute of Archaeology*, N82. USSR Academy of Sciences Press, Moscow, pp. 59–67 (in Russian).

- 977 Lyubin, V.P., Belyaeva, Y.V., Sablin, M.V., 2010. Discovery of Early Palaeolithic site in the region of Nurnus
978 paleolake (Central Armenia) In (Eds.) Studies in Archaeology of the Primitive Society of Eurasia, Collection of
979 articles dedicated to the 60 anniversary of Professor Khizri Amirkhanovich Amirkhanov. pp. 36–59 (In Russian)
- 980 Lyubin, V.P. and Balyan, S.P., 1961. New findings of Palaeolithic culture on the volcanic highlands of the
981 Armenian SSR. Report of the Armenian SSR Academy of Sciences 33. N2, pp 67–72 (In Russian).
- 982 Maddy, D., Schreve, D., Demir, T., Veldkamp, A., Wijbrans, J.R., van Gorp, W., van Hinsbergen, D.J.J., Dekkers,
983 M.J., Scaife, R., Schoorl, J.M., Stemerink, C., 2015. The earliest securely-dated hominin artefact in
984 Anatolia? Quaternary Science Reviews, 109, pp.68-75.
- 985 Martirosyan, H.A. 1970. Investigation of caves in the Hrazdan river canyon and petroglyphs in the Gegham
986 range and Shamiran. In Rbiakov, B.A. (Ed.) Archaeological Discoveries for the Year 1969. Nauka Publishing
987 House, Moscow, 384 (In Russian).
- 988 Meliksetian, K., Savov, I., Connor, C., Halama, R., Jrbashyan, R., Navasardyan, G., Ghukasyan, Y., Gevorgyan,
989 H., Manucharyan, D., Ishizuka, O. and Quidelleur, X., 2014, May. Aragats stratovolcano in Armenia-volcano-
990 stratigraphy and petrology. In EGU General Assembly Conference Abstracts (Vol. 16).
- 991 Meikle, C., Stokes, M., Maddy, D., 2010. Field mapping and GIS visualisation of Quaternary river terrace
992 landforms: an example from the Rio Almanzora, SE Spain. Journal of Maps, 6(1), pp.531–542.
- 993 Mercier, N., Valladas, H., Meignen, L., Joron, J.L., Tushabramishvili, N., Adler, D.S., Bar-Yosef, O., 2010. Dating
994 the Early Middle Palaeolithic laminar industry from Djruchula Cave, Republic of Georgia. Paléorient, pp.163–
995 173.
- 996 Messenger, E., Belmecheri, S., Von Grafenstein, U., Nomade, S., Ollivier, V., Voinchet, P., Puaud, S., Courtin-
997 Nomade, A., Guillou, H., Mgeladze, A., Dumoulin, J.P., 2013. Late Quaternary record of the vegetation and
998 catchment-related changes from Lake Paravani (Javakheti, South Caucasus). Quaternary Science Reviews, 77,
999 pp.125–140.
- 1000 Mitchell, J., Westaway, R., 1999. Chronology of Neogene and Quaternary uplift and magmatism in the
1001 Caucasus: constraints from K–Ar dating of volcanism in Armenia. Tectonophysics 304, pp. 157–186.
- 1002 Moncel, M-H., Pleurdeau, D., Pinhasi, R., Yeshurun, R., Agapishvili, T., Chevalier, T., Lebourdonnec, F-X.,
1003 Poupeau, G., Nomade, S., Jennings, R., Higham, T., Tushabramishvili, N., Lordkipanidze, D., 2015. The Middle
1004 Palaeolithic Record of Georgia: A Synthesis of the Technological, Economic and Paleoanthropological Aspects.
1005 Anthropologie L/III (1 -2), pp. 93–125.
- 1006 Montoya, C., Balasescu, A., Joannin, S., Ollivier, V., Liagre, J., Nahapetyan, S., Ghukasyan, R., Colonge, D.,
1007 Gasparyan, B., Chataigner, C., 2013. The Upper Palaeolithic site of Kalavan 1 (Armenia): An Epigravettian
1008 settlement in the Lesser Caucasus. Journal of Human Evolution, 65, pp. 621–640.
- 1009 Nalivkin, D.V., 1973. Geology of the USSR. Oliver and Boyd, Edinburgh, 855 pp (English translation from the
1010 original 1962 publication in Russian).
- 1011 Oddone, M., Bigazzi, G., Keheyan, Y. and Meloni, S., 2000. Characterisation of Armenian obsidians:
1012 Implications for raw material supply for prehistoric artifacts. Journal of Radioanalytical and Nuclear
1013 Chemistry, 243(3), pp.673–682.

- 1014 Ollivier, V., Nahapetyan, S., Roiron, P., Gabrielyan, I., Gasparyan, B., Chataigner, C., Joannin, S., Cornée, J.J.,
1015 Guillou, H., Scaillet, S., Munch, P., 2010. Quaternary volcano-lacustrine patterns and palaeobotanical data in
1016 southern Armenia. *Quaternary International*, 223, pp.312–326.
- 1017 Ollivier, V., Fontugne, M., Lyonnet, B., Chataigner, C., 2016. Base level changes, river avulsions and Holocene
1018 human settlement dynamics in the Caspian Sea area (middle Kura valley, South Caucasus). *Quaternary*
1019 *International*, 395, pp. 79-94
- 1020 Panichkina, M.Z. 1950. *Palaeolithic of Armenia*. State Hermitage Press, Leningrad (In Russian).
- 1021 Pearce, J.A., Bender, J.F., Delong, S.E., Kidd, W.S.F., Low, P.J., Guner, Y., Sargolu, F., Yilmaz, Y., Moorbath, S.,
1022 Mitchell, J.G., 1990. Genesis of collision volcanism in eastern Anatolia, Turkey. *Journal of Volcanology and*
1023 *Geothermal Research* 44, pp. 189–229
- 1024 Philip, H., Avagyan, A., Karakhanian, A., Ritz, J.F., Rebai, S., 2001. Estimating slip rates and recurrence intervals
1025 for strong earthquakes along an intracontinental fault: example of the Pambak–Sevan–Sunik fault
1026 (Armenia). *Tectonophysics*, 343(3-4), pp.205–232.
- 1027 Pickarski, N., Litt, T., 2017. A new high-resolution pollen sequence at Lake Van, Turkey: insights into
1028 penultimate interglacial–glacial climate change on vegetation history. *Climate of the Past*, 13(6), pp.689–710.
- 1029 Pickarski, N., Kwiecien, O., Djamali, M., Litt, T., 2015. Vegetation and environmental changes during the last
1030 interglacial in eastern Anatolia (Turkey): a new high-resolution pollen record from Lake
1031 Van. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 435, pp.145–158.
- 1032 Pinhasi, R., Gasparian, B., Nahapetyan, S., Bar-Oz, G., Weissbrod, L., Bruch, A.A., Hovsepyan, R., Wilkinson,
1033 K.N., 2011. Middle Palaeolithic human occupation of the high altitude region of Hovk-1, Armenia. *Quaternary*
1034 *Science Reviews*, 30(27-28), pp.3846-3857.
- 1035 Pinhasi, R., Gasparian, B., Wilkinson, K., Bailey, R., Bar-Oz, G., Bruch, A., Chataigner, C., Hoffmann, D.,
1036 Hovsepyan, R., Nahapetyan, S., Pike, A.W.G., 2008. Hovk 1 and the Middle and Upper Paleolithic of Armenia:
1037 a preliminary framework. *Journal of Human Evolution*, 55(5), pp.803–816.
- 1038 Pleurdeau, D., Moncel, M.H., Pinhasi, R., Yeshurun, R., Higham, T., Agapishvili, T., Bokeria, M., Muskhelishvili,
1039 A., Le Bourdonnec, F.-X., Nomade, S., Poupeau, G., Bocherens, H., Frouin, M., Genty, D., Pierre, M., Pons-
1040 Branchu, E., Lordkipanidze, D., Tushabramishvili, N., 2016. Bondi Cave and the Middle-Upper Palaeolithic
1041 transition in western Georgia (south Caucasus). *Quaternary Science Reviews*, 146, pp. 77–98.
- 1042 Reidel, S.P., Camp, V.E., Tolan, T.L., Martin, B.S., 2013. The Columbia River flood basalt province: stratigraphy,
1043 areal extent, volume, and physical volcanology. In: Reidel, S.P., Camp, V.E., Ross, M.E., Wolff, J.A., Martin,
1044 B.S., Tolan, T.L., Wells, R.E. (Eds.), *The Columbia River Flood Basalt Province*. Geological Society of America
1045 *Special Paper*, 497, pp. 1–43.
- 1046 Reilinger, R.E., McClusky, S.C., Oral, M.B., King, R.W., Toksoz, M.N., Barka, A.A., Kinik, I., Lenk, O., Sanli, I.,
1047 1997. Global Positioning System measurements of present-day crustal movements in the Arabia-Africa-
1048 Eurasia plate collision zone. *Journal of Geophysical Research: Solid Earth*, 102(B5), pp.9983–9999.
- 1049 Rust, B.R., 1978. A classification of alluvial channel systems. In: A.D. Miall (Editor), *Fluvial Sedimentology*.
1050 *Canadian Society of Petroleum Geologists Memoirs*, 5, Calgary, pp. 187–198.

- 1051 Sardaryan, S.H. .1954. Palaeolithic in Armenia. Armenian SSR Academy of Sciences Press, Yerevan (In
1052 Russian).
- 1053 Sheth, H., Meliksetian, K., Gevorgyan, H., Israyelyan, A., Navasardyan, G., 2015. Intracanyon basalt lavas of
1054 the Debed River (northern Armenia), part of a Pliocene–Pleistocene continental flood basalt province in the
1055 South Caucasus. *Journal of Volcanology and Geothermal Research*, 295, pp.1–15.
- 1056 Stockhecke, M., Kwiecien, O., Vigliotti, L., Anselmetti, F.S., Beer, J., Çağatay, M.N., Channell, J.E., Kipfer, R.,
1057 Lachner, J., Litt, T., Pickarski, N., 2014. Chronostratigraphy of the 600,000 year old continental record of Lake
1058 Van (Turkey). *Quaternary Science Reviews*, 104, pp.8-17.
- 1059 von Suchodoletz, H., Gärtner, A., Hoth, S., Umlauf, J., Sukhishvili, L., Faust, D., 2016. Late Pleistocene river
1060 migrations in response to thrust belt advance and sediment-flux steering—The Kura River (southern
1061 Caucasus). *Geomorphology*, 266, pp. 53-65
- 1062 Tolan, T.L., Beeson, M.H., 1984. Intracanyon flows of the Columbia River Basalt Group in the lower Columbia
1063 River Gorge and their relationship to the Troutdale Formation. *Geological Society of America Bulletin*, 95(4),
1064 pp.463–477.
- 1065 Tushabramishvili, N., Pleurdeau, D., Moncel, M.H., Agapishvili, T., Vekua, A., Bukhsianidze, M., Maureille, B.,
1066 Muskhelishvili, A., Mshvildadze, M., Kapanadze, N., Lordkipanidze, D., 2011. Human remains from a new
1067 Upper Pleistocene sequence in Bondi Cave (western Georgia). *Journal of Human Evolution*, 62(1), pp.179–
1068 185.
- 1069 Vekua, A., Lordkipanidze, D., 1998. The Pleistocene paleoenvironment of the Transcaucasus [Le
1070 paléoenvironnement pléistocène du Caucase]. *Quaternaire*, 9(4), pp.261–266.
- 1071 Valder, J.F., Carter, J.M., Medler, C.J., Thompson, R.F., Anderson, M.T., 2018. Hydrogeologic framework and
1072 groundwater conditions of the Ararat Basin in Armenia (No. 2017-5163). US Geological Survey.
- 1073 Walker, G.P.L., 1973. Mount Etna and the 1971 eruption-Lengths of lava flows. *Philosophical Transactions of*
1074 *the Royal Society of London. Series A, Mathematical and Physical Sciences*, 274(1238), pp.107–118.
- 1075 White, J.D., Ross, P.S., 2011. Maar-diatreme volcanoes: a review. *Journal of Volcanology and Geothermal*
1076 *Research*, 201(1–4), pp.1–29.
- 1077 Wood, C.A., 1980. Morphometric evolution of cinder cones. *Journal of Volcanology and Geothermal*
1078 *Research*, 7(3–4), pp.387–413.
- 1079 Yeritsyan, B.G., 1975. The New Lower Palaeolithic cave site Lusakert 1 (Armenia). In Kruglikova, I.T. (Ed.) *Briefs*
1080 *of the Institute of Archaeology*, 141, Nauka Publishing House, Moscow, pp.54–67 (in Russian).
- 1081 Yeritsyan B.G., Korobkov, I.I., 1979. Study of Palaeolithic Sites in the Middle Stream of Hrazdan river.
1082 *Archaeological Discoveries for the Year 1978*, Nauka Publishing House, Moscow, 519–520 (in Russian).
- 1083 Zamyatnin, S.N., 1950. Study of the Palaeolithic period in the Caucasus for the years 1936–1948. *Materials*
1084 *for the Study of the Quaternary Period 2*, pp. 127–139 (In Russian).

1085 **10. Supplementary Information, Figures and Tables**

1086 **Supplementary Information 1.** GIS database of outcrop locations and lava flow distributions

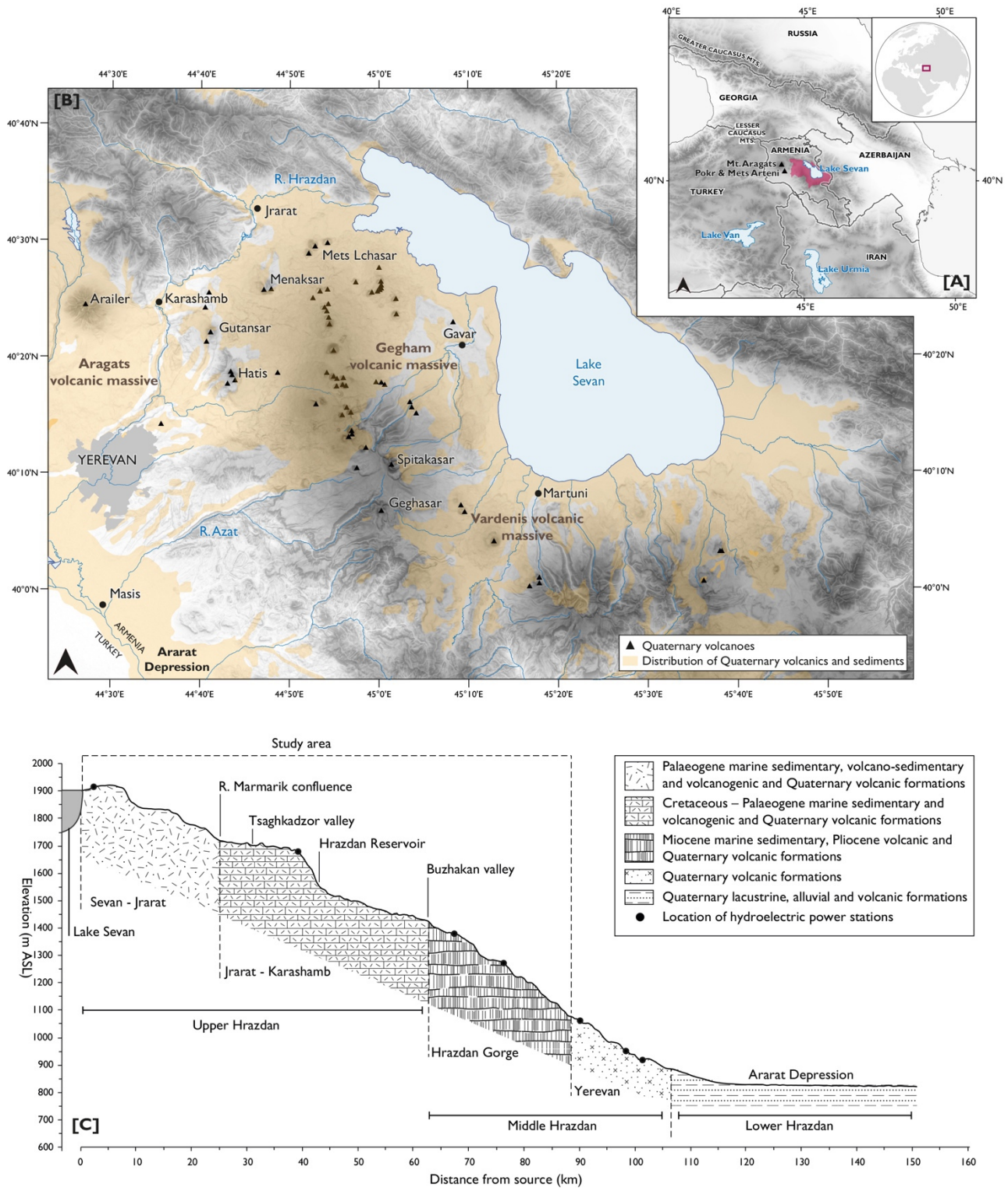
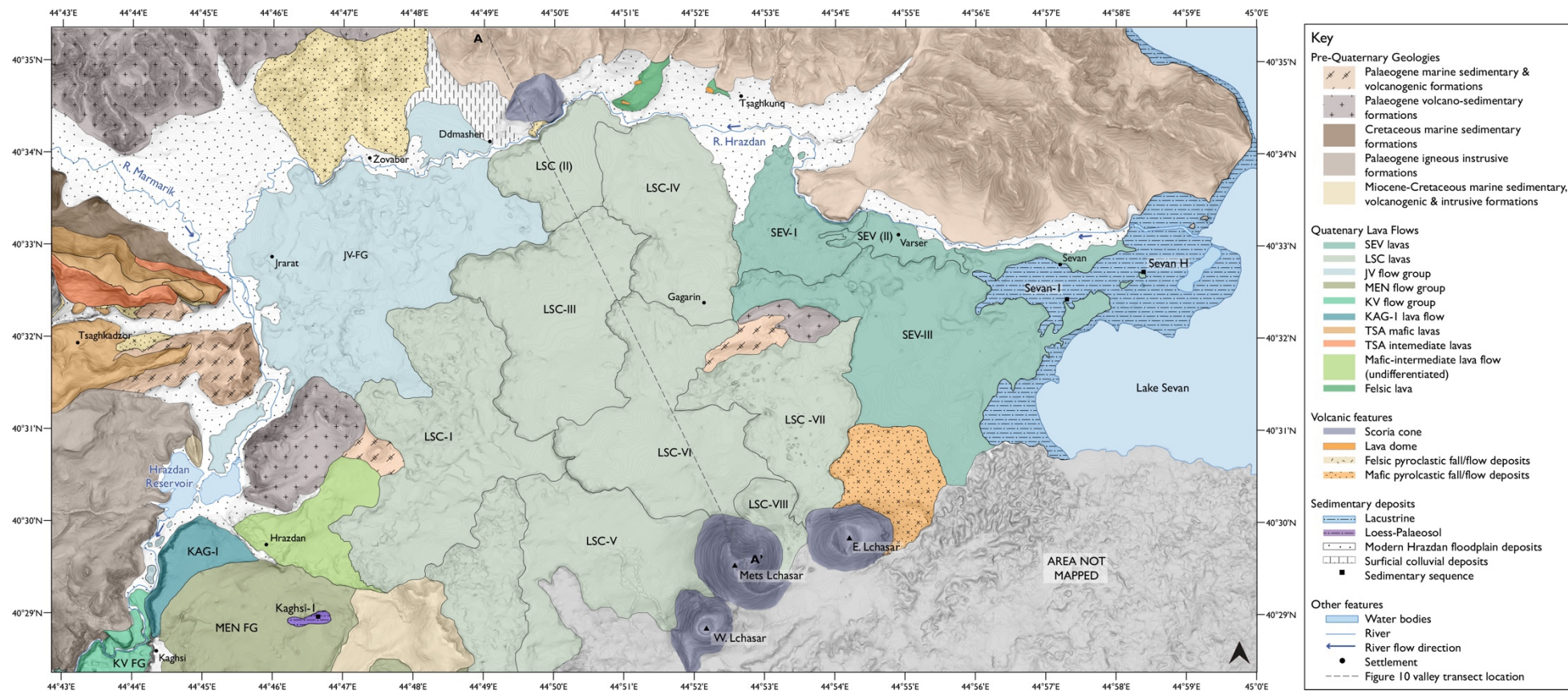
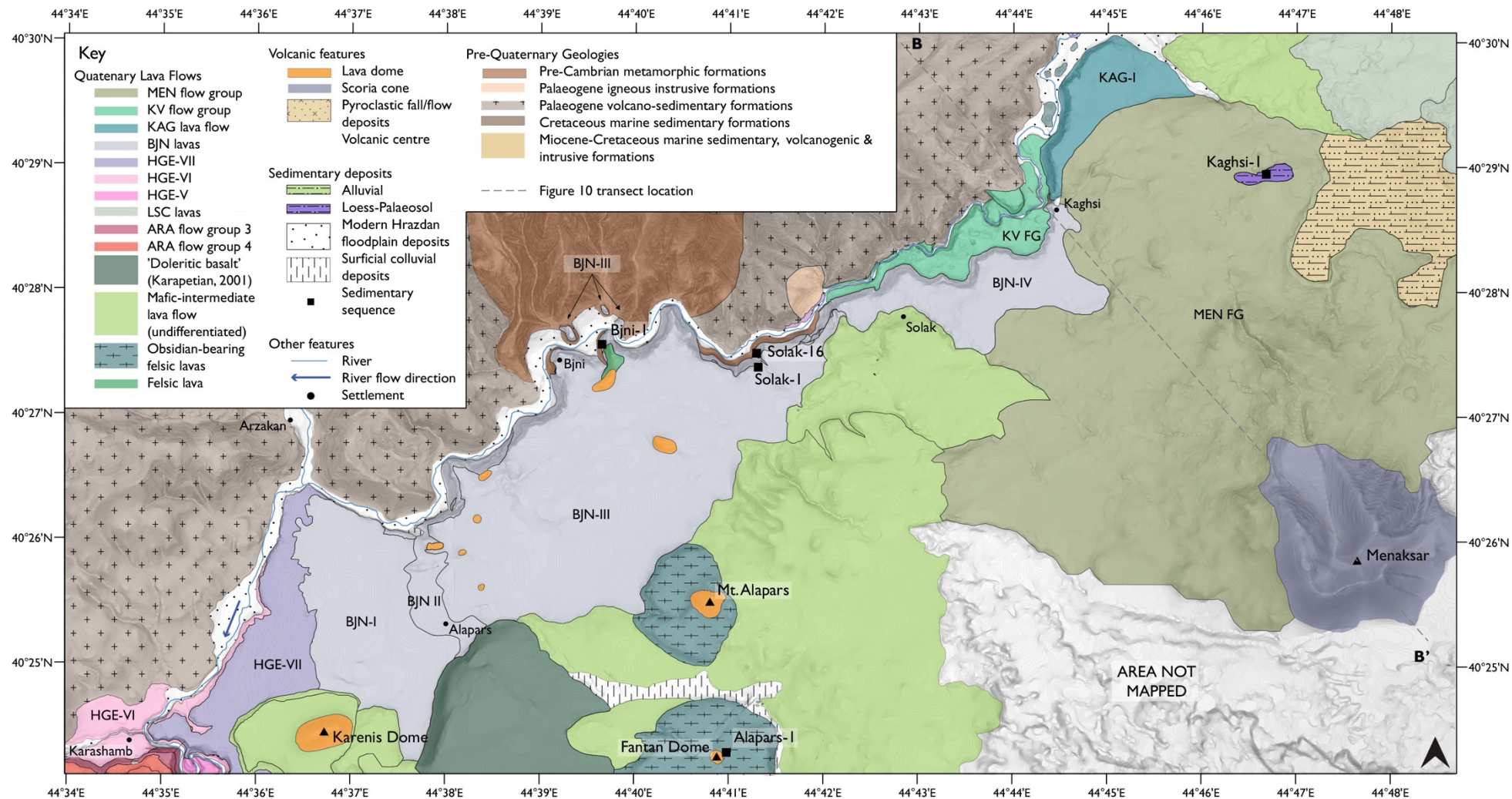


Figure 1. (A) Topographic map of the Southern Caucasus with the location of the Hrazdan catchment (in red), (B) Overview map of the study area, with the position of Quaternary volcanoes and the distribution of Quaternary volcanic and sedimentary formations (adapted from Kharazyan, 2007), and (C) Schematic elevation (m asl) profile of the Hrazdan valley with the broad geologic subdivision referred to in-text, the extent of the study area, and locations of hydroelectric power stations.



1093
1094 **Figure 2.** Geological map of the Sevan-Jrarat reach in the Upper Hrazdan valley.



1095

1096

Figure 3. Geological map of the Jrarat-Karashamb reach in the Upper Hrazdan valley.

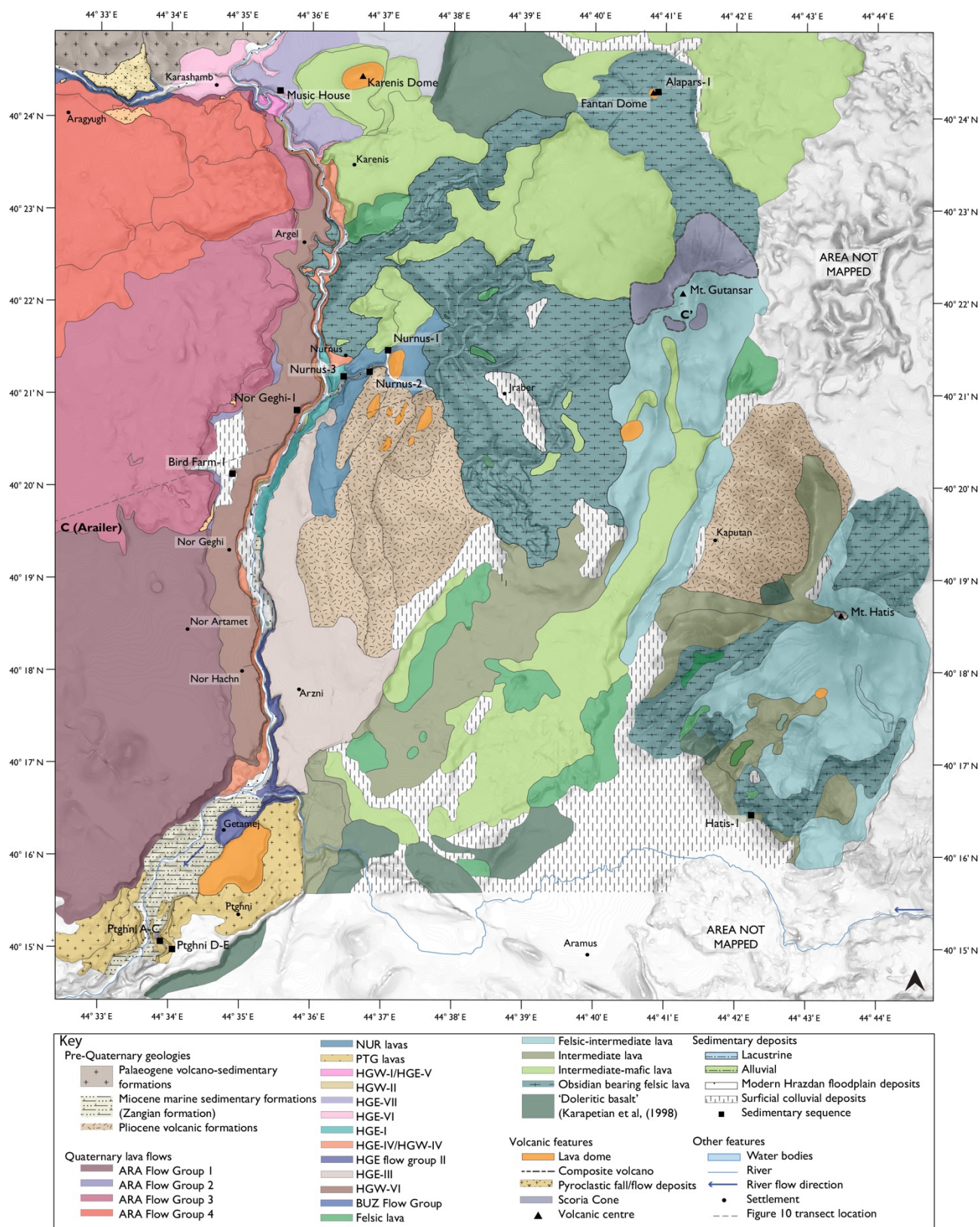


Figure 4. Geological map of the Hrazdan Gorge and NW Gegham Range in the Middle Hrazdan valley. Geological mapping around Hatis and Gutansar edifices adapted from Karapetian (1968) and Karapetian et al., (2001).

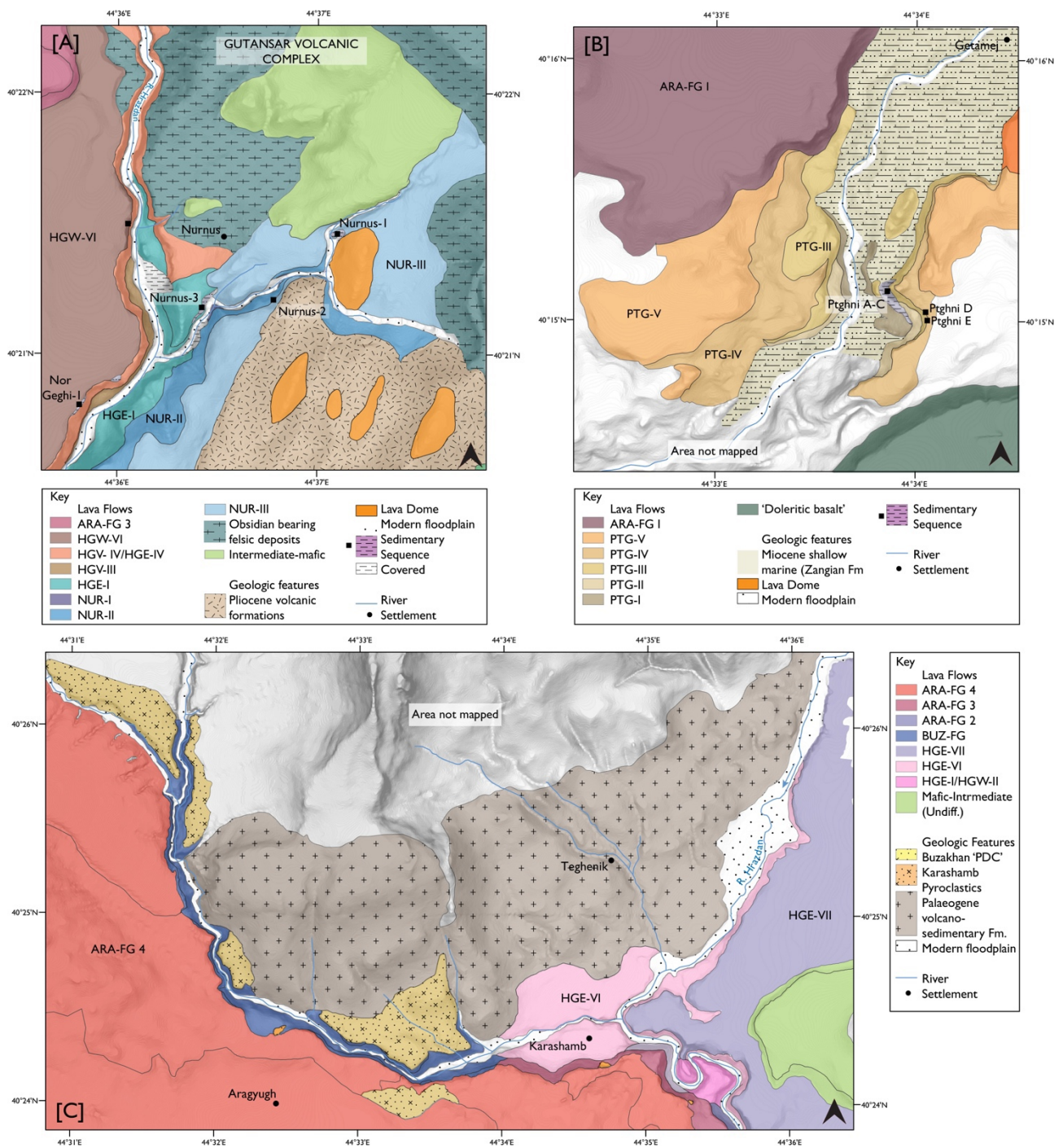
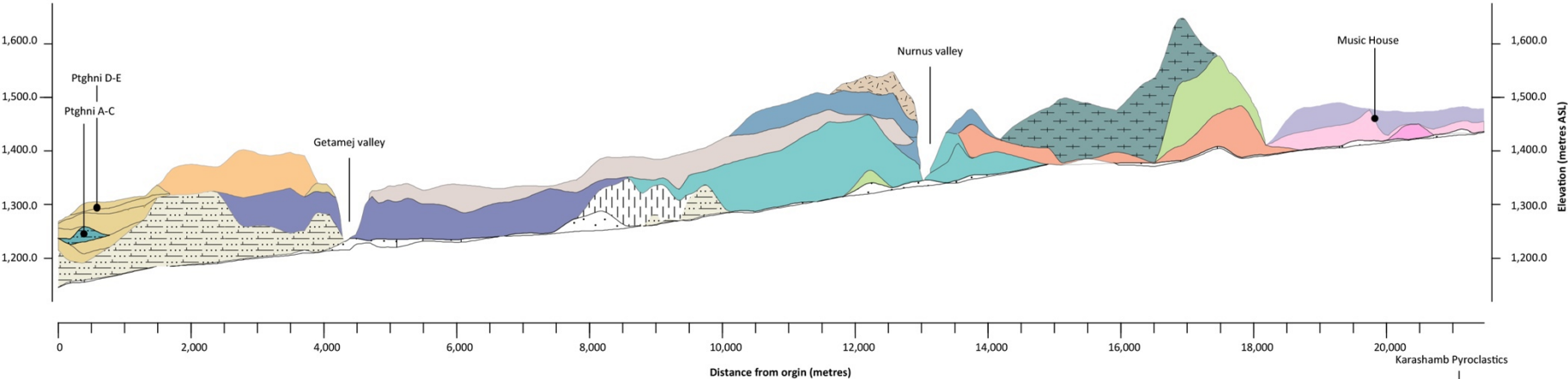


Figure 5. Geological map showing the distribution and position of sedimentary sequences, lava flows and other volcanogenic deposits in (A) the Nurnus valley, Hrazdan Gorge, (B) the reach of the Hrazdan Gorge around Ptghni, and (C) the NW sector of the Hrazdan Gorge and Buzhakan valley.

Hrazdan Gorge eastern profile



Hrazdan Gorge western profile

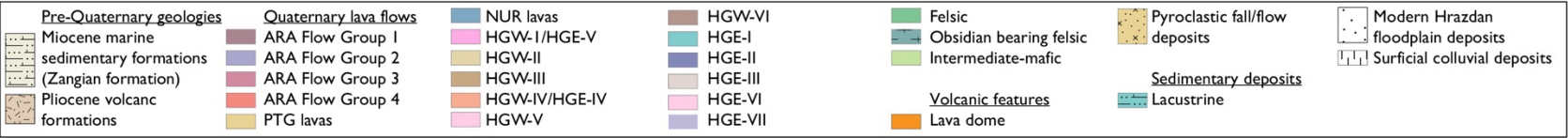
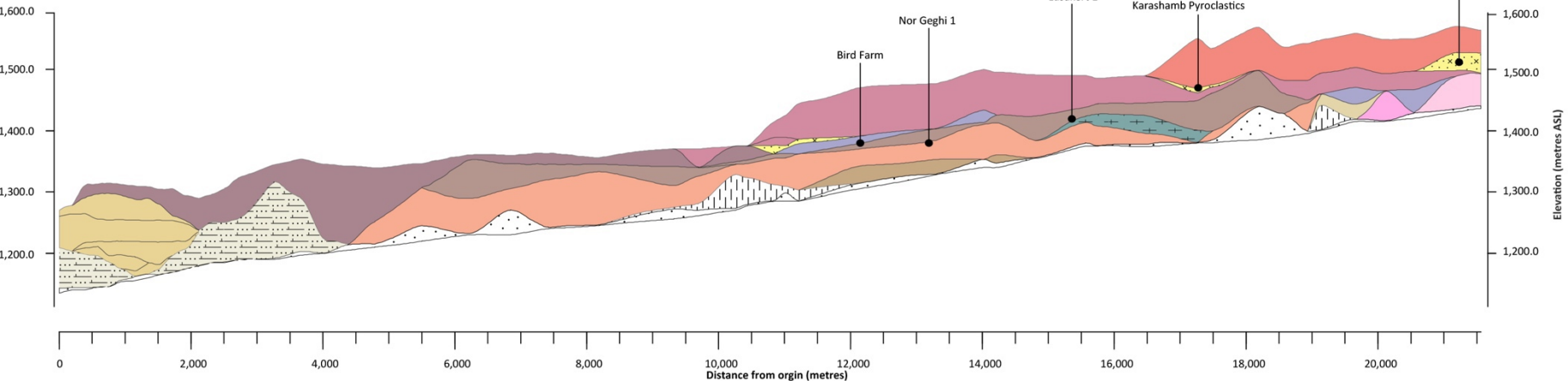
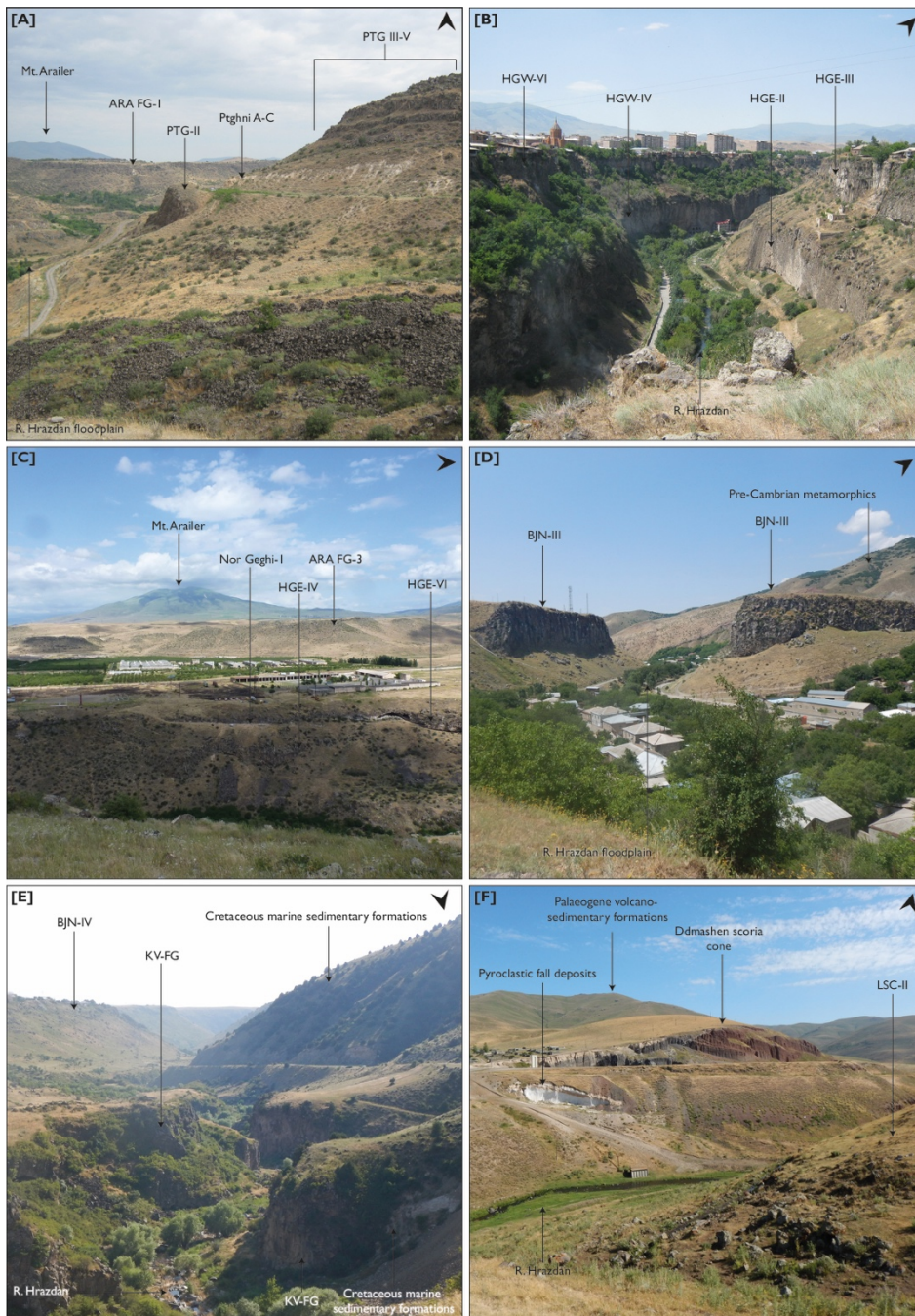


Figure 6. Schematic longitudinal profiles of the (A) east and (B) west side of Hrazdan Gorge showing the position (m asl) of lava flows and sedimentary sequences exposed along the gorge sides.



1109

1110 **Figure 7.** Photographs showing geomorphological setting in the Hrazdan valley. Highlighted are geological
 1111 units, location of the modern Hrazdan river and, where appropriate, lava flow names. North arrow located
 1112 in the top right corner of each image. Locations are (A) Ptghni, where several flows are found with
 1113 interbedded lacustrine-alluvial sediments (Ptghni A–C), (B) the Hrazdan Gorge around Arzni, (C) the western
 1114 side of the Hrazdan Gorge, showing the relative position of gorge lava flows, Arailer and Arailer lava flows,
 1115 and the Nor Geghi 1 archaeological site, (D) the Hrazdan valley at Bjni, (E) Hrazdan valley at Kaghsi, showing
 1116 higher elevation BJN flow and lower elevation lavas infilling the valley floor, and (F) Hrazdan valley at
 1117 Ddmashen, showing the location of scoria cone, pyroclastic deposits and the northernmost extent of the LSC
 1118 lava flows. Photograph credit, A, B, D–F: J. Sherriff; C: M, Knul.

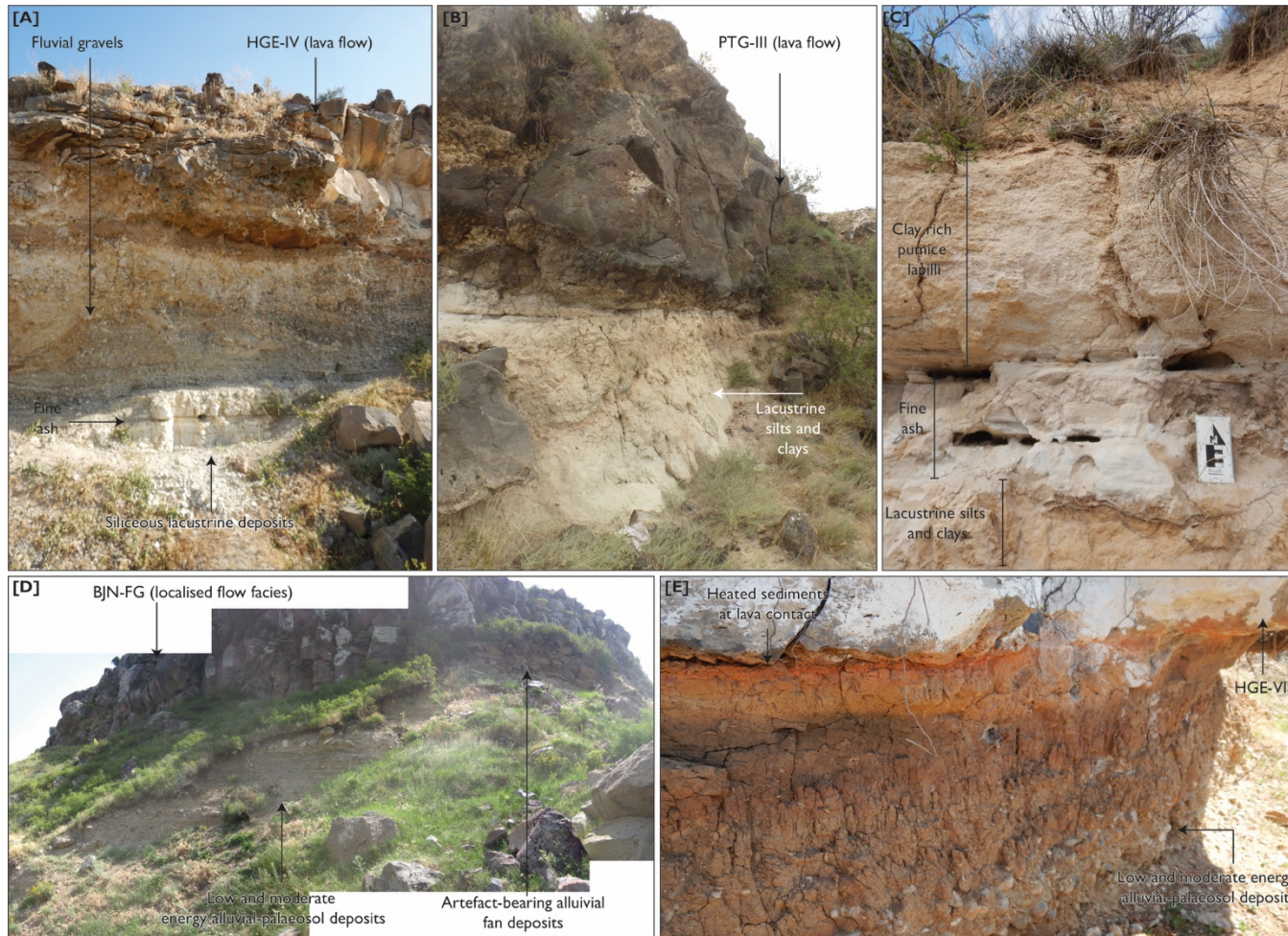
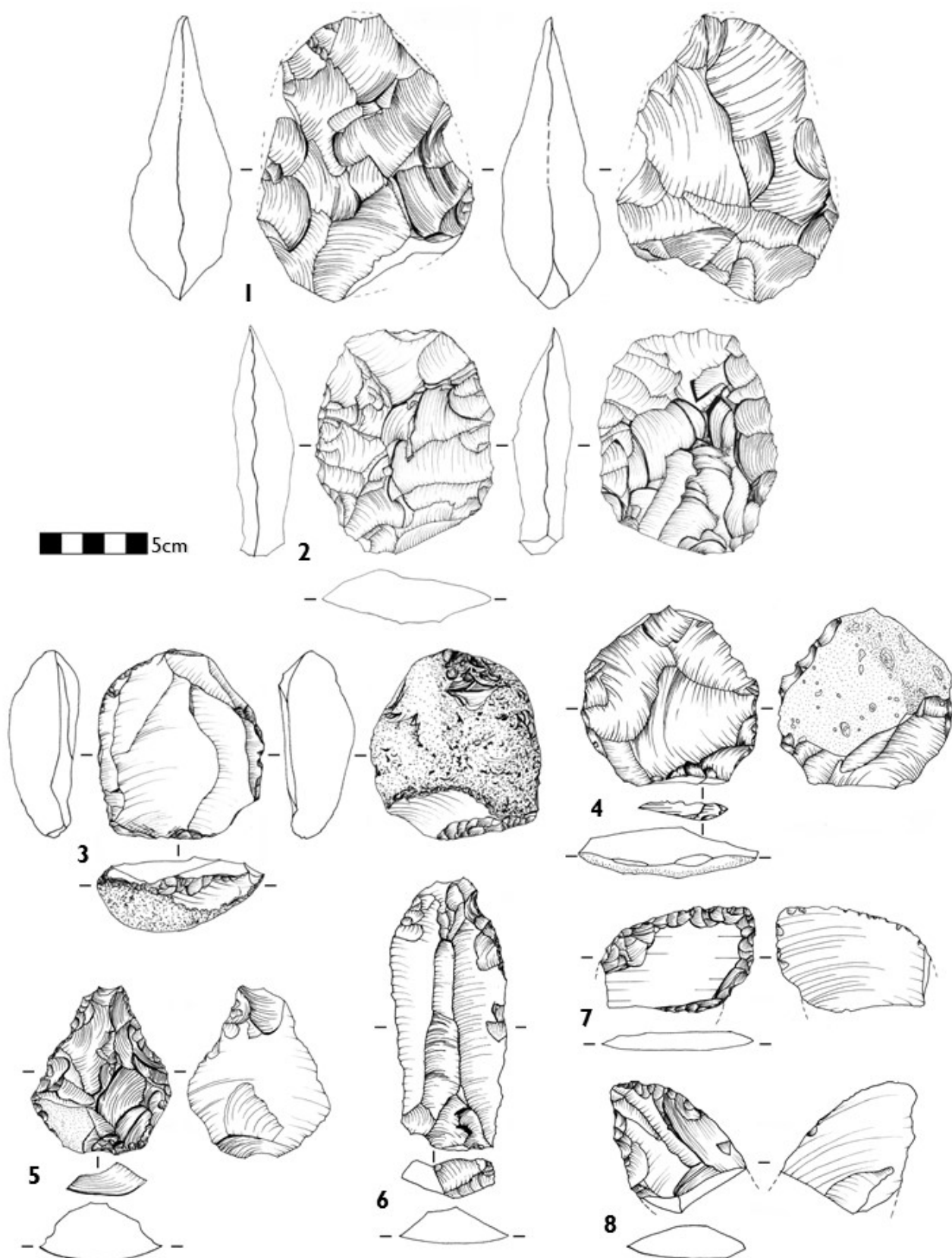


Figure 8. Representative sedimentary sequences in the Hrazdan valley (A) Bird Farm1, (B) Ptghni D–E, C) Nurnus3, (D) Solak 16 (not visible in the photograph is the Upper Palaeolithic site of Solak 1 which is located on the plateau above Solak 16), and (E) Music House. Sedimentological and stratigraphic summaries of these sequences is presented in Table 3. Photograph credit: A,C,E - J. Sherriff; B - M. Knul; D - E. Beverly.



1123

1124

1125

Figure 9. Sample of obsidian areifacts from Nor Geghi 1, 1–2 bifaces, 3–4 Levallois cores, 5 thick convergent scraper with edge and tip damage, 6 retouched point, 7–8, déjeté scrapers.

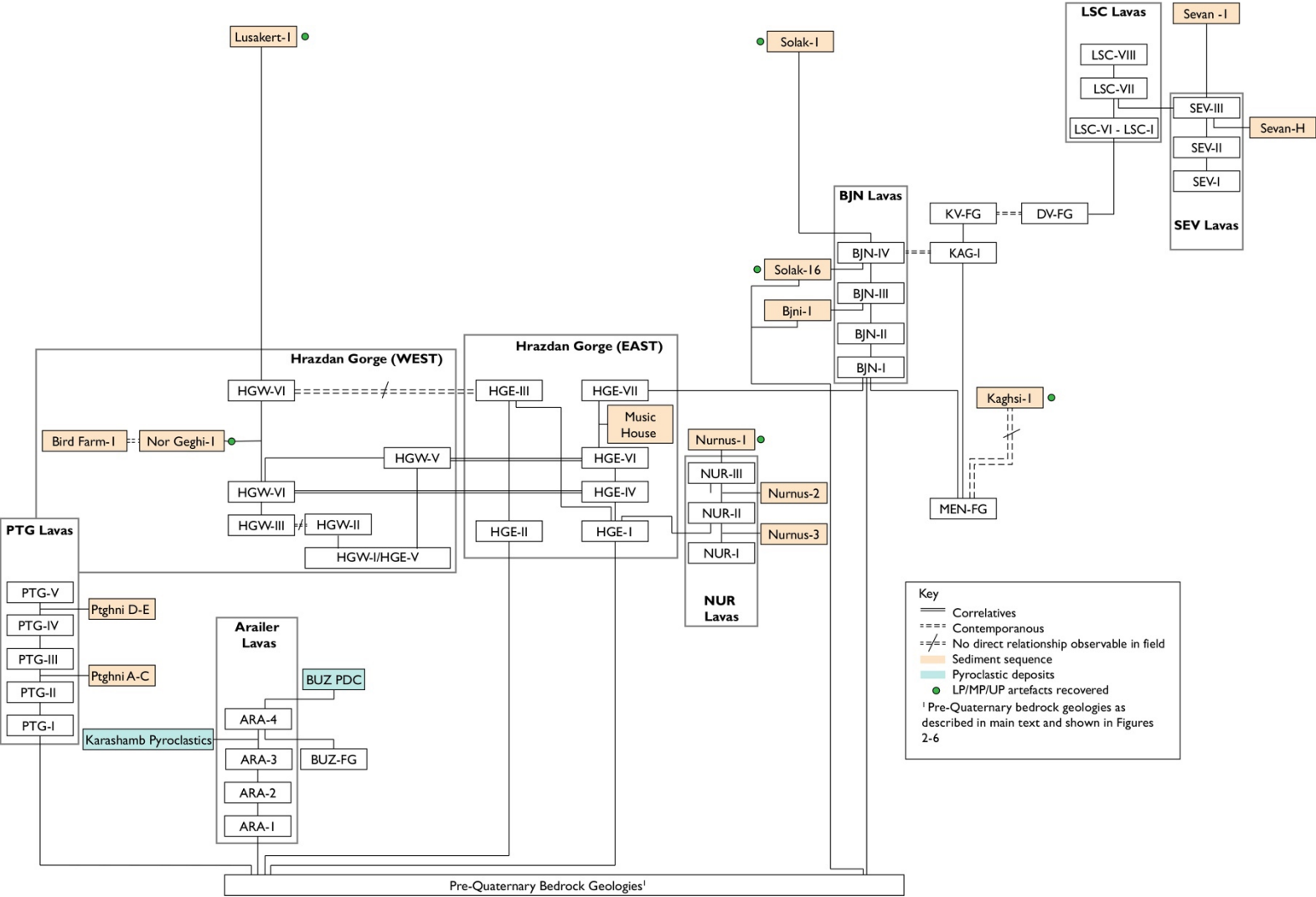


Figure 10. Harris matrix (Harris, 1979), showing the relative stratigraphic relationships between lava flows, sedimentary sequences, archaeological sites and other volcanic features in the Hrazdan valley based on geomorphic and geological mapping presented in this study.

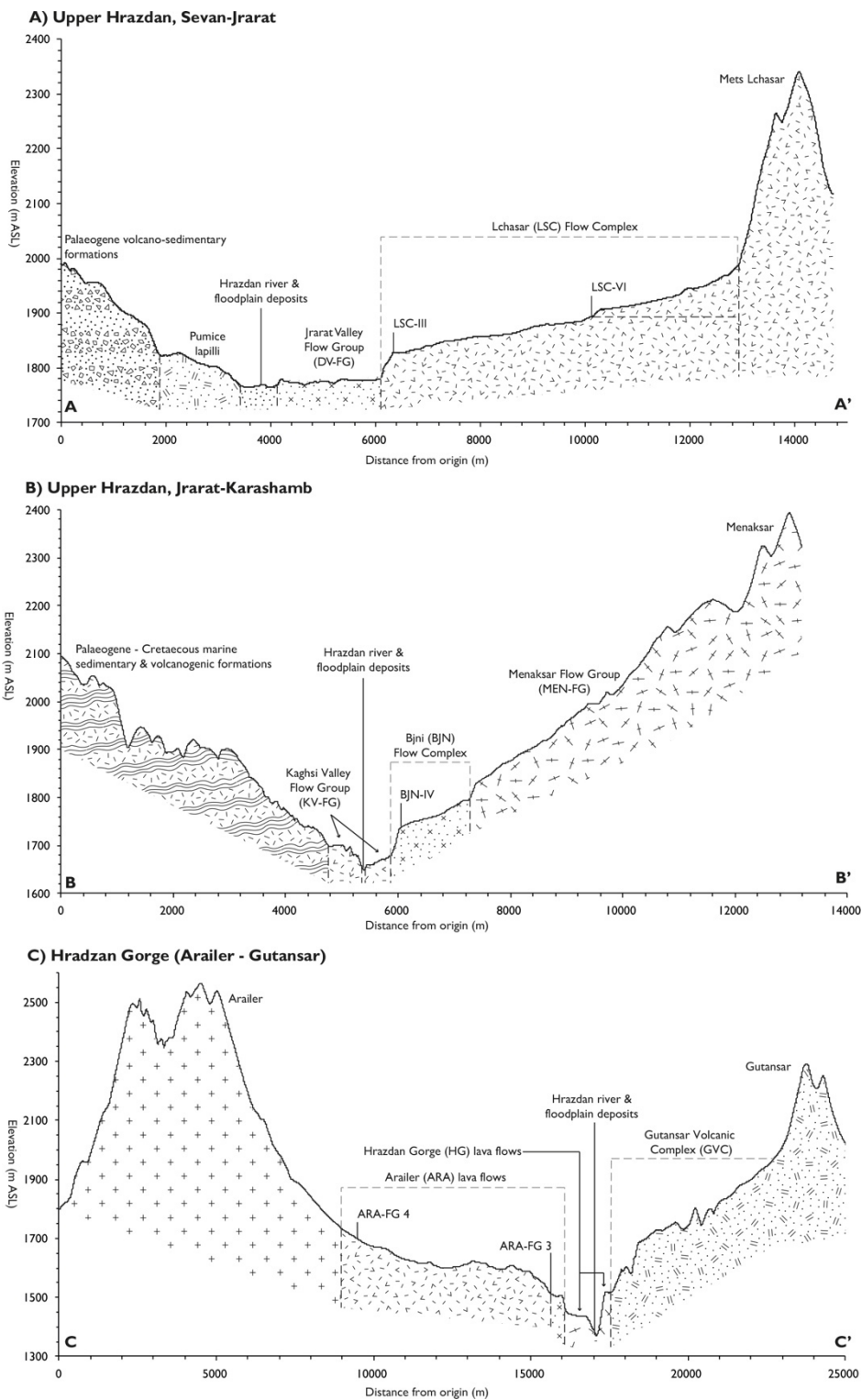


Figure 11. Schematic cross-sectional topographic profiles of the Hrazdan valley in the (A) Upper Hrazdan, Sevan-Jrarat reach, (B) Upper Hrazdan, Jrarat-Karashamb reach, and (C) Middle Hrazdan (Hrazdan Gorge) between Arailer and Gutansar volcanic centres. Shown are the principal lava flow groups and lava complexes, basement geologies and location of the Hrazdan river and modern floodplain deposits. The subsurface relationships between these deposits are not shown. Locations of cross sections are shown in Figures 2, 3, and 4.

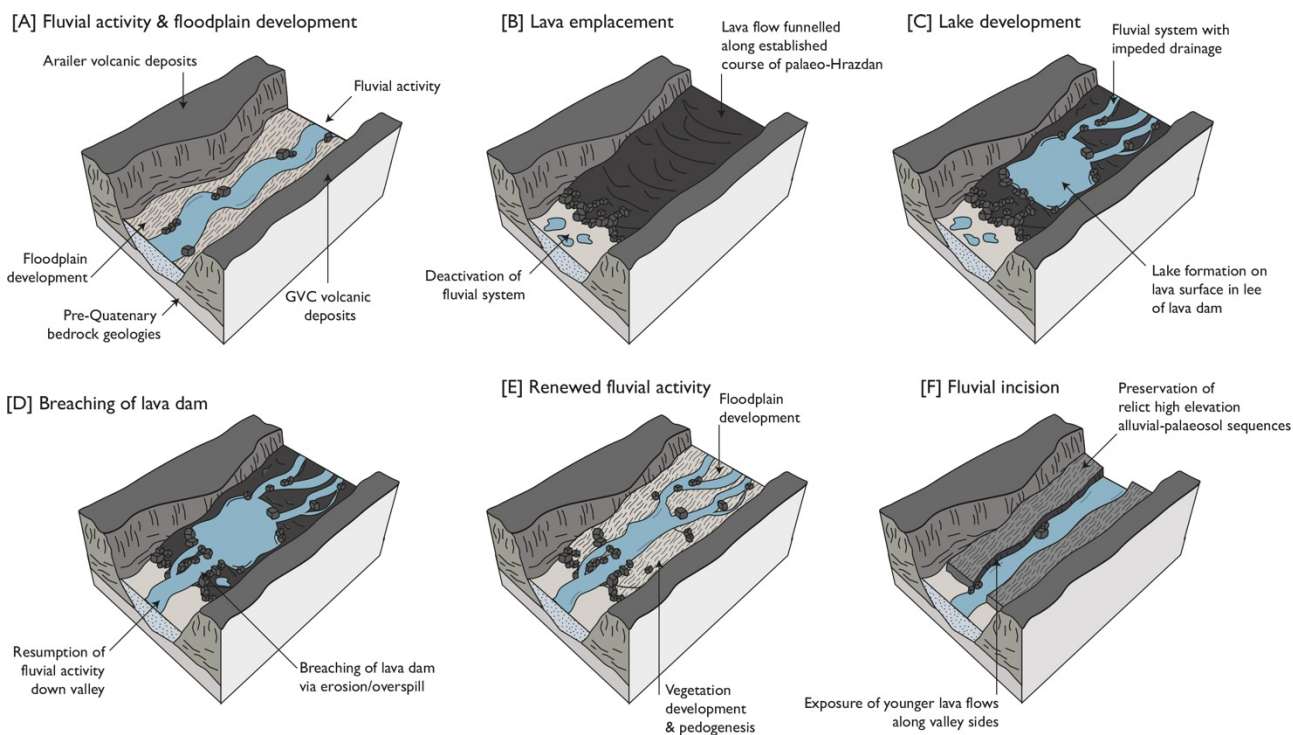
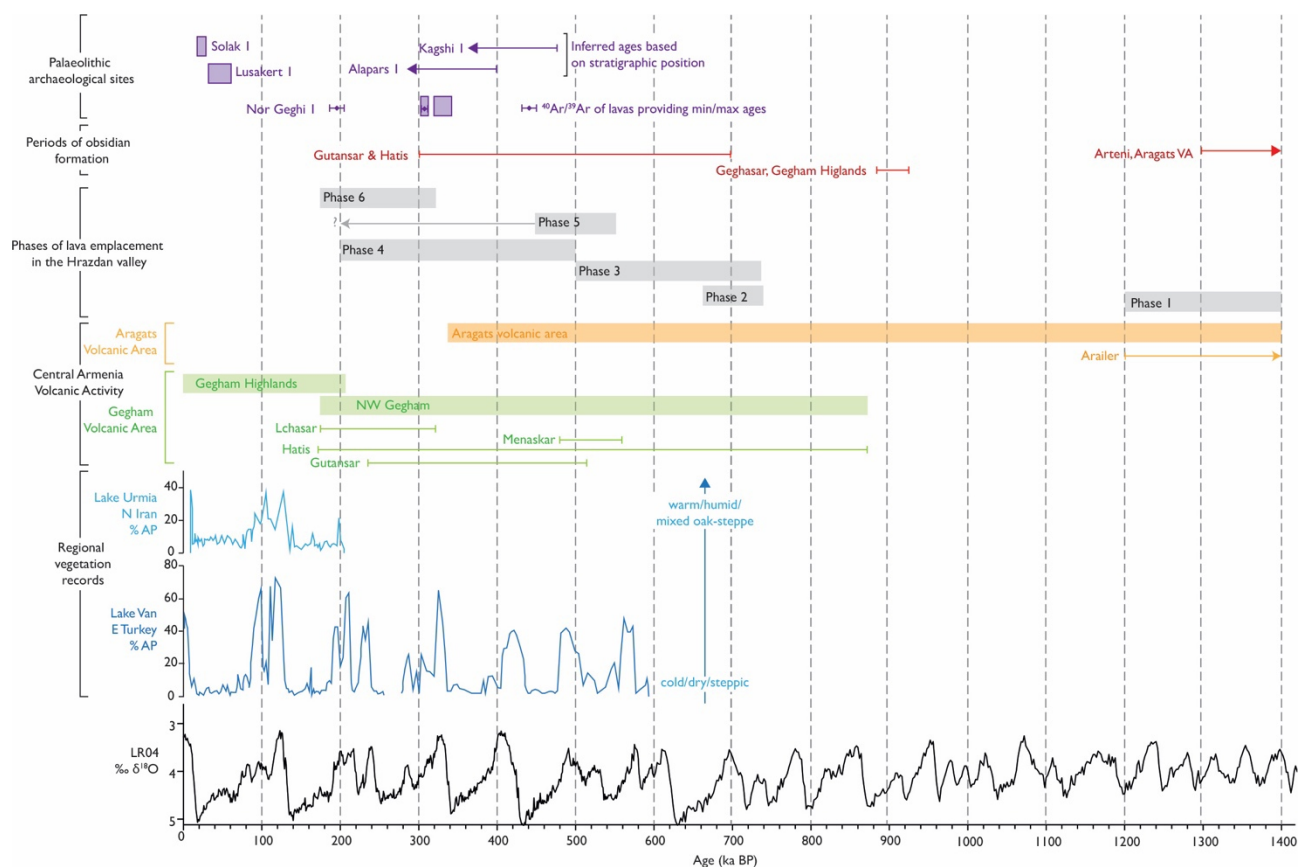


Figure 12. Model of landscape evolution in the Hrazdan Gorge. Several stages are clear based on the geomorphic and sedimentary record. (A) Fluvial activity and floodplain development in the palaeo-Hrazdan valley, (B) volcanic activity, resulting in emplacement of lava along the course of the valley, (C) impeded fluvial drainage as a consequence of lava emplacement, resulting in the development of lacustrine systems on the newly formed land surface, (D) breaching and/or over spill in the lava dam causing the reactivation of the Hrazdan fluvial system, (E) fluvial activity, floodplain development and relative landscape stability, (6) fluvial incision as a consequence of base level change and tectonic activity, resulting in the exposure of younger lava infilling the valley and preservation of high elevation alluvial sequences.



1146

1147

1148

1149

1150

1151

Figure 13. Summary diagram showing the phases of volcanic activity and lava emplacement in the Hrazdan valley as described in the text, based on lithostratigraphy and chronological evidence. Also shown are absolute and inferred ages of key archaeological sequences in the area, and the suggested timing of obsidian formation in the area (Frahm et al., 2014a,b). These are plotted against marine benthic $\delta^{18}\text{O}$ stack (Lisecki and Raymo, 2005) and arboreal pollen % form Lake Van (Litt et al., 2014) and Lake Urmia (Djmali et al., 2008).

1152 **Table 1.** Summary of chronological data from the Upper and Middle Hrazdan valley between Lake Sevan and Yerevan. In table references are: 1= Lebedev et al.,
1153 2013; 2= Lebedev et al., 2011; 3= Oddone et al., 2001; 4 = Badalian et al., 2001; 5 = Karapetian et al., 2001; 6 = Adler et al., 2014; 7 = Mitchell and Westaway, 1999.
1154 Age Error notation is: * 1 σ uncertainty, ** 2 σ uncertainty, *** uncertainty reported but unpublished sigma (σ) , - no data reported.

Sample Code	Location	Geological setting	Grid Reference	Technique	Material	Age (ma)	Uncertainty	Refs
Arairer volcanic centre (Aragats volcanic area)								
G110/03	Arairer	Volcanic centre; lava flow	40°17'5.1"N, 44°40'3.6"E	K-Ar	Rhyolite	0.47	0.03**	1
Ar1/07	Arairer	Volcanic centre; lava flow (base of southern slope)	40°21'49.5"N, 44°27'34.8"E	K-Ar	Andesite	1.32	0.05**	2
Ar3/07	Arairer	Volcanic centre; lava flow (base of southern slope)	40°22'53.3"N, 44°27'54.2"E	K-Ar	Andesite	1.28	0.06**	2
Ar6/07	Arairer	Volcanic centre; lava flow (middle of southern slope)	40°23'31.4"N, 44°27'22.2"E	K-Ar	Dacite	1.29	0.03**	2
Ar7/07	Arairer	Volcanic centre; lava flow (middle of southern slope)	40°23'36.1"N, 44°27'18.2"E	K-Ar	Dacite	1.3	0.05**	2
Ar9/07	Arairer	Volcanic centre; lava flow (upper part of southern slope)	40°23'45.5"N, 44°27'12.9"E	K-Ar	Dacite	1.28	0.04**	2
Ar11/07	Arairer	Volcanic centre; lava flow (upper part of southern slope)	40°23'42.2"N, 44°27'22"E	K-Ar	Dacite	1.35	0.05**	2
Ar13/07	Arairer	Volcanic centre; lava flow (base of eastern slope)	40°23'56.4"N, 44°29'40.7"E	K-Ar	Dacite	1.23	0.03**	2
Ar15/03	Arairer	Volcanic centre (eastern summit)	40°24'10.5"N, 44°28'5.3"E	K-Ar	Dacite	1.37	0.04**	2
Ar17/07	Arairer	Volcanic centre (summit)	40°24'11.2"N, 44°27'52.7"E	K-Ar	Dacite	1.36	0.04**	2
Gutansar volcanic complex (NW Gegham Volcanic area)								
ALA 02	Alapars	Lava Dome (Gutansar volcanic complex)		FT	Obsidian	0.23	0.02*	3
ALA 03	Alapars	Lava Dome (Gutansar volcanic complex)		FT	Obsidian	0.2	0.03*	3

ALA 3	Alapars	Lava Dome (Gutansar volcanic complex)		FT	Obsidian	0.28	0.03*	4
ALA 4	Alapars	Lava Dome (Gutansar volcanic complex)		FT	Obsidian	0.31	0.02*	4
28G/01	Jraber	Obsidian within 'Jraber extrusion'	40°22'30.1"N, 44°36'29.3"E	K-Ar	Obsidian	1.2	0.5**	2
Font Av	Fantan	Lava dome (Gutansar volcanic complex)		FT	Obsidian	0.32	0.02*	4
Font Au 3	Fantan	Lava dome (Gutansar volcanic complex)		FT	Obsidian	0.3	0.02*	4
29G/01	Fantan	Lava dome (Gutansar volcanic complex)	40°24'39.7"N, 44°41'17.4"E	K-Ar	Rhyolite	0.48	0.05**	2
1675	Gutansar	Volcanic centre (Gutansar Volcanic Complex)		K-Ar	-	0.55	-	5
1675	Gutansar	Volcanic centre (Gutansar Volcanic Complex)		FT (?)	-	0.33	-	5
GUT 01	Gutansar	Volcanic centre (Gutansar Volcanic Complex), SW flank of volcano		FT	Obsidian	0.33	0.02*	3
GUT 02	Gutansar	Volcanic centre (Gutansar Volcanic Complex), SW flank of volcano		FT	Obsidian	0.27	0.02*	3
Gut 1	Gutansar	Volcanic centre (Gutansar Volcanic Complex)		FT	Obsidian	0.32	0.03*	4
Kap E 2	Gutansar	Volcanic centre (Gutansar Volcanic Complex)		FT	Obsidian	0.25	0.03*	4
Gi 1	Gutansar	Volcanic centre (Gutansar Volcanic Complex)		FT	Obsidian	0.31	0.03*	4
G117/03	Gutansar	Volcanic centre (Gutansar Volcanic Complex)	40°21'31.4"N, 44°40'47.5"E	K-Ar	Rhyolite	0.9	0.3*	1
19G/01	Gutansar	Volcanic centre (Gutansar Volcanic Complex), lava flow	40°19'7.3"N, 44°41'9.4"E	K-Ar	Rhyolite	0.38	0.06**	1

Hatis volcanic centre								
1161	Hatis	Volcanic centre		K-Ar	-	0.65	-	5
1161	Hatis	Volcanic centre		FT (?)	-	0.33	-	5
Zer W Sup 2	Hatis	Obsidian from rhyolite-perlite flows		FT	Obsidian	0.21	0.04*	4
Agu W Sup 3	Hatis	Obsidian from rhyolite-perlite flows		FT	Obsidian	0.34	0.04*	4
Xian Xian	Hatis	Obsidian from rhyolite-perlite flows		FT	Obsidian	0.4	0.03*	4
13G/01	Hatis	Volcanic centre; south slope	40°17'17.7"N, 44°41'6.6"E	K-Ar	Rhyolite	0.66	0.04**	1
14G/01	Hatis	Volcanic centre; south slope	40°17'12.8"N, 44°41'4.4"E	K-Ar	Obsidian	0.74	0.25**	1
24G/01	Hatis	Volcanic centre; summit	40°18'13.5"N, 44°43'8.2"E	K-Ar	Rhyolite	0.7	0.03**	1
25G/01	Hatis	Volcanic centre; summit	40°18'28.8"N, 44°43'31.1"E	K-Ar	Rhyolite	0.77	0.12**	1
15G/01	Hatis	Volcanic centre; Dyke on south slope	40°16'27.3"N, 44°42'5.2"E	K-Ar	Obsidian	0.48	0.05**	1
26G/01	Hatis	volcanic centre; dyke on summit	40°18'43.7"N, 44°43'15.3"E	K-Ar	Obsidian	0.48	0.04**	1
17G	Tekblur (Hatis)	Lava flow (S slopes of Hatis)	40°18'37.7"N, 44°40'45.1"E	K-Ar	Basaltic trachyandesite	0.56	0.05**	1
Hrazdan Valley Lavas								
BF Basalt 1 1	Bird Farm	Lava flow above sedimentary sequence (HGW-VI)	40°20'9.4"N, 44°34'53.1"E	Ar-Ar	Basalt (groundmass)	0.195	0.008*	This study
BF Basalt 1 2	Bird Farm	Lava flow above sedimentary sequence (HGW-VI)	40°20'9.4"N, 44°34'53.1"E	Ar-Ar	Basalt (groundmass)	0.198	0.007*	This study
NG1 Basalt 1	Nor Geghi 1	lava flow overlying sedimentary sequence (HGW-VI)	40°20'48.6"N, 44°35'49.9"E	Ar-Ar	Basalt (groundmass)	0.197	0.007*	6

NG1 tephra	Nor Geghi 1	Tephra within sedimentary sequence (unit 1)	40°20'48.6"N, 44°35'50"E	Ar-Ar	Ash (sanidine)	0.308	0.003*	6
NG1 Basalt 7	Nor Geghi 1	Lava flow underlying sedimentary sequence (HGW-IV)	40°20'48.7"N, 44°35'50.1"E	Ar-Ar	Basalt (groundmass)	0.441	0.006*	6
1A1	Yerevan	Lava flow		K-Ar	Basalt	1.12	0.08*	7
33G/01	Yerevan	Lava flow	40°11'30.1"N, 44°28'49.2"E	K-Ar	Latite	0.53	0.04**	1
34G/01	Yerevan	Lava flow	40°11'11.9"N, 44°30'6.7"E	K-Ar	Mugearite	0.56	0.04**	1
NW Gegham volcanic features								
965	Avazan	Lava dome (rhyolite-dacite)		K-Ar	-	4.7	0.2***	5
968	Gyumush	Lava dome (rhyolite-dacite)		K-Ar	-	4.8	0.5***	5
GYU 02	Gyumush	Lava dome (rhyolite-dacite)		FT	Obsidian	0.22	0.02*	3
GYU 04	Gyumush	Lava dome (rhyolite-dacite)		FT	Obsidian	0.23	0.02*	3
NUR 01	Nurnus	Obsidian outcrop		FT	Obsidian	0.23	0.02*	3
NUR 03	Nurnus	Obsidian outcrop		FT	Obsidian	0.26	0.02*	3
G73/03	Menaksar (Kovasar)	Dyke (N of summit)	40°27'6.9"N, 44°47'14.1"E	K-Ar	Trachydacite	0.54	0.02**	1
G74/03	Menaksar (Kovasar)	Volcanic centre (N of summit)	40°26'24.8"N, 44°46'41"E	K-Ar	Mugearite	0.53	0.03**	1
G70/03	Lchasar (Boghusar)	Volcanic centre	40°29'44.7"N, 44°53'8.3"E	K-Ar	Mugearite	0.25	0.035**	1

1156 **Table 2.** Criteria used for desktop-based identification of geomorphic landforms in the Hrazdan valley. References are as follows: 1 = Fisher and Schmicke, 1984,
1157 1971; 2 = Wood, 1980; 3 = White and Ross, 2011; 4 = Fink and Anderson, 2000; 5 = Jerram 2002; 6 = Lockwood and Lipman, 1980; 7 = Walker, 1973; 8 = Harris, 2015;
1158 9= Jerram and Petford, 2011; 10= Folch, 2012; 11= De Silva and Lindsay, 2015; 12= Rust, 1978; 13= Meikle et al., 2010

Feature	Morphology	GIS identification	Uncertainties	Significance	Refs.
Volcanic landforms (monogenetic landforms and features)					
Scoria cone	Symmetrical conical-shaped feature with bowl-shaped crater at the apex, formed of pyroclastic material (primarily scoria lapilli). Slope angle ranges from 25–38°, height:width ratio 0.18–0.26.	Dark/light shadowing shows positive relief. Slope angle and height:width ratios consistent with morphology. Distinctive black/red colouration of exposed scoria on satellite imagery.	Vegetation and weathering of features cause difficulty in distinguishing from lava domes. Need to be distinguished in the field.	Regularly found in association with 'basaltic' volcanic fields.	1,2,3
Endogenous & exogenous lava domes	Dome-shaped protrusion resulting from slow extrusion of high viscosity lava. Variable morphology. May be tabular-steep sided in cross section, and circular-elliptical – irregular in plan view.	Dark/light shadowing indicates positive relief. Circular-elliptical form, with clear boundary between surrounding material. Height:length ratio of 0.5–0.3.	Vegetation and weathering of features cause difficulty in distinguishing from scoria cones. Need to be distinguished in the field.	Extrusions related to a larger composite cone or caldera. May be located along faults.	4
Lava flows and fields	Accumulations of lava-forming plateaus of varying surface roughness. Many have complex lobate structure at front of flow. Surface texture (if fresh) can be used to differentiate between 'a'ā, pāhoehoe and block lava flows.	Shadowing indicates lava field front with slope angle of 20–30°. Low-moderate surface roughness based on lava texture. Superposition of several identifiable flows. Higher elevation than modern floodplain.	Modification of flows by weathering and fluvial activity. Lava structure and mineralogy needs to be distinguished in the field.	Emplacement of lava associated with effusive volcanic activity. Spatially extensive flows have stratigraphic significance.	5, 6, 7, 8

Undifferentiated volcanogenic deposits	Covers a broad range of features associated with effusive and explosive (pyroclastic density currents, pyroclastic fall deposits, tephra).	Distinctive white colouration of terrain on satellite imagery.	Differentiation of type of deposit not possible using imagery. Best identified in the field.	Indication of interval of explosive and effusive volcanism, spatially extensive deposits enable correlation across wide area.	7, 9, 10
Volcanic landforms (polygenetic landforms and features)					
Polygenetic volcanic centres - composite volcanoes	Conical-shaped edifice, with basal diameter ranging from 10–20 km, slope angle of ca. 30° and height:width ratio of 0.15—0.33. Formed by multiple eruptions from single or migrating vent. Symmetrical-asymmetrical.	Dark/light shadowing shows positive relief. Slope angle and height:width ratios consistent with morphology. Occurrence of large central or several central craters.	Modification by post-eruptive processes. Association of cones and lava domes complicate morphology.	Reflect potential sources of lava flows/fields and pyroclastic deposits. Can be used in conjunction with lava flow/field morphology to elucidate relationship.	11
Fluvial landforms and features					
River terrace	Bench/step along valley side with flat top and step fore edge. May be paired or unpaired with opposite valley side.	Shadowing indicates terrace fore edge. High slope angle of fore edge, flat upper surface.	Field differentiation of bedrock and alluvial terrace	Marks former position of river and associated floodplain/ deposits. Can be used to estimate rate of incision.	12, 13
Floodplain deposits	Flat accumulations of fine grained alluvial sediment located on and around channel margins of modern river systems	Flat surface with low surface roughness. Occurs at similar elevation to modern river course.	May represent a lower bedrock terrace. Frequently masked by vegetation and infrastructure.	Marks extent of river in its current position.	12

1160 **Table 3.** Summary of the sedimentary and archaeological sequences identified in the Hrazdan valley. BA= Bronze Age, UP = Upper Palaeolithic, MP = Middle
1161 Palaeolithic, LP = Lower Palaeolithic, UD = undiagnostic. In-table references are: 1 = this study, 2 = Adler et al., 2012, 3 = Adler et al., 2014, 4 = Lyubin et al., 2010, 5
1162 = Frahm et al., 2017. Locations of sequences are shown in Figures 2–5.

Site	Location	Elevation (m ASL)	Sedimentary description	Stratigraphic context	Archaeology	Refs.
Sevan 1	40°32'18.5"N, 44°57'9.3"E	1930	2m-thick sequence of carbonate-rich silts and clays with cm-scale interbeds of shell-rich sand and fine ash. Base of sequence not reached.	Abuts lava flow SEV-III near modern shore of Lake Sevan	Pottery fragments (BA)	1
Sevan H	40°32'41.9"N, 44°58'22.4"E	1930	1.5m-thick sequence of horizontally bedded volcanoclastic pumice lapilli, sand, silt and fine ash. Base of section not exposed	Underlies SEV-III lava flow	-	1
Kaghsi 1	40°28'54.4"N, 44°46'43.6"E	1872	Approximately 200m long, 10–20m thick sequence of pedogenically modified Aeolian and colluvial deposits, with at least 6 distinct pedocomplexes identified. Present within sequence are 6 primary fine-medium ashes. Artefacts recovered from colluvial deposits in western edge of sequence. Base of sequence not reached.	Sequence location indicates it likely overlies MEN-FG lavas. However lower contact between sediments and underlying strata is not observable the field.	Lithics (MP)	1
Solak 1	40°27'25.8"N, 44°41'16.7"E	1634	1.0–1.5m-thick sequence of fine-grained colluvium containing a mature soil (Bt and Bk horizons) and resting on lava. UP artefacts are found throughout the sequence.	Sequence overlies BJN-III (BJN lava complex)	Lithics (UP)	1
Solak 16	40°27'31.3"N, 44°41'11.9"E	1580	30m-thick alluvial-palaeosol sequence comprising beds of pedogenically modified silty sand and clast rich gravel deposits. Sequence is capped by moderately sorted angular gravels presenting alluvial fan deposition. Undiagnostic obsidian artefacts recovered from the upper alluvial fan strata.	Overlies Precambrian metamorphic basements rocks and is capped by BJN-FG (BJN Lava Complex)	Lithics (UD)	1
Bjni 1	40°27'30"N, 44°39'35.3"E	1544	1m tripartite sequence composed of moderately sorted angular gravels of principally metamorphic lithologies (colluvium), fine-medium ash, and silt-sand (alluvium).	Overlies Precambrian metamorphic basements rocks and is capped by BJN-III (BJN Lava Complex)	-	1

Lusakert1	40°22'18.6"N, 44°35'49.8"E	1427	Separate sequences within and outside the rockshelter. The former comprises 3–4m of floodplain deposits overlain by colluvium, and the latter of 1–2m of first channel sediments then cave earths. Archaeological artefacts and features, and vertebrate remains are associated with the cave earths and floodplain alluvium	Rock shelter within HGW-VI in the Hrazdan Gorge.	Vertebrate remains, Lithics (MP)	2
Alapars 1	40°24'17.4"N, 44°40'52"E	1798	6m-thick sequence comprising from the base upwards fluvial reworked pumice, gravels forming in fluvial environment, pedogenically modified floodplain alluvium, calcrete and pedogenically modified aeolian deposits. Artefacts recovered from alluvium, aeolian deposits and modern soil [derived]).	Sequence found in association with Fantan Dome (part of GVC). Exact stratigraphic relationship unclear.	Lithics (MP)	1
Bird Farm 1	40°20'9.2"N, 44°34'52.1"E	1388	Comprises from the base upwards: tephric silt-sand, primary scoria lapilli, reworked scoria lapilli and sand, siliceous silt-clay lacustrine deposits with interbedded fine ash, cross and planar bedded clast rich gravels (principally mafic igneous lithologies, pedogenically modified silt-sand. Sequence capped by mafic lava (HGW-VI) which has been $^{40}\text{Ar}/^{39}\text{Ar}$ dated to 195 ± 8 ka and 198 ± 7 ka.	Sequence underlies HGW-VI. On W side of Hrazdan Gorge. Contact between sequence and underlying strata not visible.	-	1
Nor-Geghi 1	40°20'48.2"N, 44°35'49.8"E	1402	1–5m-thick sequence of (from base upwards) floodplain deposits in which a mature palaeosol has developed, high-energy fluvial deposits and a further floodplain sequence in which a second palaeosol has developed. Artefacts have been recovered from the upper floodplain deposits and associated palaeosol, and sand facies of the channel sediments.	Sediment sequence and archaeological artefacts are sandwiched between HGW IV and HGW VI	Lithics (LP/MP)	3
Music House	40°24'15.5"N, 44°35'35.9"E	1486	1m-thick sequence of pedogenically modified silt-sand and clast rich gravels representing alluvial sedimentation.	Interbedded between HE-VII and HGE-VI.	-	1
Nurnus 1	40°21'28.1"N, 44°37'8.3"E	1539	5m+ sequence of clay-rich lake sediment overlain by diatomite and coarse fluvial deposits (tabular gravels and sands), above mafic lava.	Overlies NUR-III in Nurnus Valley.	Vertebrate remains	4
Nurnus 2	40°21'11.3"N, 44°36'45.4"E	1483	2m sequence of heavily weathered lacustrine silt-clay with plant imprints and discontinuous fine ash.	Underlies NUR-III in Nurnus valley. Contact with underlying strata not visible.	-	1

Nurnus 3	40°21'7"N, 44°22'17.6"E	1406	4m-thick sequence comprising from the base upwards; fine sand-silt (lacustrine), pumice lapilli, silt-clay with pumice lapilli fragments (lacustrine with reworked volcanics), fine sand-silt with interbedded fine-medium ash (lacustrine).	Underlies (NUR-II in Nurnus valley. Contact with underlying strata not visible.	-	1
Hatis 1	40°16'26.2"N, 44°42'11.5"E	1571	1.5 m-thick coarse-grained colluvial sequence derived from volcanic deposits to the north. LP artefacts including bifaces found throughout.	None, but sediments derived from obsidian-bearing rocks to the north	Lithics (LP)	1
Ptghni D–E	40°15'2.4"N, 44°34'2.8"E	1294	1m-thick sequence of massive silt-sand. Lower and upper contact with lavas is visible.	Interbedded with PTG-III (cf. LF PTG 3) and PTG-VI (cf. LF PTG 2).	-	5
Ptghni A–C	40°15'7.6"N, 44°33'49.8"E	1253	29m-thick sequence of alluvial lacustrine deposits comprising pedogenically modified silt and sand with obsidian clasts, overlain by horizontally bedded silts and clays, which in turn is overlain by fine-sand silt. Lower and upper contact with lavas is visible.	Interbedded with PTG-I (cf. LF PTG 5) and PTG-II (cf. LF PTG 3)	-	5