Article:
Halama, R, Meliksetian, K, Savov, IP orcid.org/0000-0003-4218-4365 et al. (2 more authors) (Cover date: May/June 2020) Pinched between the plates: Armenia's voluminous record of volcanic activity. Geology Today, 36 (3). pp. 101-108. ISSN 0266-6979

https://doi.org/10.1111/gto.12309

Pinched between the plates: Armenia's voluminous record of volcanic activity

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Located in the heart of the Lesser Caucasus mountains, where the Arabian and Eurasian tectonic plates collide, Armenia occupies an exceptional geological position shaped through millions of years of subduction and collision. It is a unique place on Earth recording extensive intrusive and volcanic activity related to the long-standing continental convergence. The volcanoes of Armenia provide a rare opportunity to study the sources and processes involved in this unusual type of magmatism. More than 500 Quaternary volcanoes have been mapped in Armenia, most of them formed from single eruptive episodes. Among several large composite volcanoes, the mighty Aragats stands out as the largest volcano in Armenia and the region altogether. Volcanic deposits testify to the range of eruptive styles - from the ignimbrites formed in eruptions as explosive and voluminous as any seen globally in the modern era to the enormous fissure-fed lava flows that form the Southern Caucasus flood basalt province, the smallest and youngest Large Igneous Province in the world. Several pre-historical and historical eruptions have been documented, highlighting the potential for future volcanic activity in the region. In recent years, research has focused on the volcanic hazards associated with the Armenian National Power Plant (ANPP), located in the foothills of Aragats volcano. This article highlights some of the extraordinary volcanic and intrusive features

observed in Armenia and summarises aspects of recent volcanological and petrological research.

High and fiery –Armenia's geographical position and volcanic past

Armenia, or Hayastan in Armenian, is a small, landlocked country in the South Caucasus, dotted with volcanoes (Fig. 1). This country with an area of ~30000 km^2, roughly the size of Belgium, is not only the world's first state to adapt Christianity as official religion in AD 301, but also sports an outstanding geological history affected by collisional tectonics. Most visitors to Armenia arrive by plane in Yerevan, located at 1000 m above sea level, 1800 km from Moscow and 3600 km from London. On a clear day, one can relish the views of Ararat, the national symbol of Armenia located in the present-day territory of Turkey. The Ararat volcanic complex comprises the large, nearly perfect cones of the Greater Ararat and Lesser Ararat stratovolcanoes (Fig. 2).

Yerevan lies in the Armenian Highlands, bordered by the Anatolian plateau to the west and the Iranian plateau to the southeast. Taken together, this region forms a high plateau stretching from Turkey through Armenia into Iran, 500 km wide and 2000 km long. The vast Turkish-Armenian-Iranian plateau is in fact part of the Alpine-Himalayan orogenic belt that has been uplifted following the collision of Arabia with the Eurasian continent. The uplift has been attributed to upwelling of hot asthenosphere following detachment of previously subducted slabs or mantle lithosphere, combined with crustal shortening.

The heritage of the volcanic activity is evident in Yerevan and many other Armenian cities, where varieties of volcanic tuffs are extensively used as building stones (Fig. 2). Many of the volcanoes in the region were active in the Holocene (11700 years ago until present): Süphan and Nemrut near Turkey's Lake Van, Ararat, volcanic centres in the Gegham, Vardenis and Syunik volcanic highlands of Armenia, the Samsari volcanic ridge in Georgia as well as Damavand in Iran. Nemrut has an eruption recorded in 1441, while a phreatic eruption at Ararat in 1840, triggered by a strong earthquake, has been reconstructed based on eyewitness accounts who described ballistic projectiles and a pyroclastic flow.

Despite Ararat's proximity to Yerevan (Fig. 2), the geologists exploring Armenia will struggle to get close to the volcano – the border between Armenia and Turkey is closed and heavily guarded. As much as one can enjoy Armenia's geological and cultural riches, the country's political situation remains difficult, and the view across the border to Ararat serves as a sober reminder of the unresolved disputes between the two countries.

Magmatism through the ages in a setting of continental convergence

Two major plate collisions shaped Armenia's geological past: During Late Cretaceous-Early Eocene times (ca. 70-60 million years ago [Ma]), a continental fragment referred to as South Armenian Block (SAB) collided with the Eurasian continental margin. Some 40-30 million years ago, the Arabian plate collided with the SAB, now amalgamated to the Eurasian margin, producing a second collisional event. This long-lasting continental convergence was accompanied by waxing and waning magmatic activity.

A period of major magmatism in Armenia lasted from ~49 to ~38 Ma and comprised the emplacement of a variety of igneous rocks, including alkaline and nepheline-bearing gabbros, monzonites and syenites as well as gabbro-diorite-granodiorite-syenogranite complexes, granites and volcanic rocks. The Tezhsar volcano-intrusive alkaline ring complex, located a few km to the SE of Vanadzor, is dated at ~41 Ma and represents a unique occurrence of silica-undersaturated, alkaline igneous rocks in a setting of continental convergence. Spectacular specimens of pseudoleucite crystals, up to several centimetres across, can be found here. In southeast Armenia, syn-magmatic porphyry Cu-Mo mineralization formed at 44-40 Ma in the Meghri–Ordubad and Bargushat plutons. These plutons cover an area of 1400 km^2 and form the largest pluton cluster in the Lesser Caucasus. A second stage of Cu-Mo porphyry formation associated with high-K calc-alkaline and shoshonitic magmatism occurred around 27-26 Ma, coinciding with Arabia-Eurasia collision to post-collision tectonics. Magmatism continued until ~21 Ma with the emplacement of granitoid plutons during the final stages of the Neotethyan subduction and the main Arabia-Eurasia collision. There was subsequently limited magmatic activity until the Late Miocene, when mantle-derived magmatism increased again and remained important until the present day.

Aragats volcano: From Ara's throne to Semiramis' plateau

According to Armenian legend, the Assyrian queen Semiramis, or "Shamiram" in Armenian, staged a war against Armenia just to get hold of the legendary and apparently exceptionally beautiful Armenian hero Ara the Beautiful. The Armenian words "ara" and "gah" translate as Ara's throne, giving the name of Armenia's largest volcano, Aragats, that was active from 1.5 to 0.5 Ma. Another, slightly older Upper Pliocene – Early Pleistocene (ca. 3.6-0.8 Ma) stratovolcano, Arailer (Ara's mountain) is neighbouring Aragats, located between the Hrasdan and Kasakh river valleys. From a volcanologist's perspective, Ara must have been a happy man, as the two volcanoes, Aragats and Arailer, have much to offer in terms of volcanic features, a fascinating volcanological evolution and more than a little raw natural beauty.

Perhaps most prominent its enormous size: A huge shield volcano ~42 km in diameter, Aragats reaches a height of 4090 m, a mere 45 km from the capital Yerevan, and represents the largest volcanic complex in the Lesser Caucasus. Aragats overlooks the Shamiram Plateau, which is characterised by numerous monogenetic cinder cones (Fig. 3). Aragats does not quite reach the height of neighbouring Ararat (5137 m), but by far outclasses its neighbour in terms of its volume of magma produced.

The eruptive history of Aragats comprises mafic and intermediate lava flows but also features dacitic domes in the summit area as well as several major ignimbrite-forming eruptions documented in the stratigraphic record of the surroundings (Fig. 3). Ignimbrites, formed by pyroclastic density currents and tephra fallout from Aragats, cover an area of ~5000 km^2 around the volcano and the largest eruptive volumes reached 5 km^3 corresponding to a Volcanic Explosivity Index (VEI) $\geq$ 5. These major eruptions of Aragats were similar in size to the eruptions of Vesuvius in AD 79 or Pinatubo in 1991. All ignimbrites are Quaternary in age, with an older group (1.8-0.9 Ma) being distinct from a younger group dated to about 0.75-0.65 Ma (Middle Pleistocene). Many buildings in Yerevan are constructed using ignimbrite, which is strong enough to support multi-storey buildings and is considered as a favourable building stones due to its light weight and good insulating properties. Recent dating shows that the youngest eruptions of Aragats occurred some 0.5 million years ago as lava flows at the Irind and Tirinkatar cones on the flanks of the volcano.

Quaternary volcanism in Armenia

Whereas Aragats and the adjacent Arailer represent individual volcanic edifices, the Gegham, Vardenis and Syunik volcanic highlands in central and southeast Armenia can be described as distributed volcanic fields, mostly comprising monogenetic vents with relatively few central volcanoes (Fig. 1). These distinct volcanic features illustrate key differences between central volcanoes and volcanic fields. Aragats has maintained a magma supply through its conduit for a long time, indicating the persistence of a long-lived thermal anomaly. It has erupted repeatedly, producing magmas of different compositions, and is hence referred to as polygenetic. In contrast, the volcanic fields are dominated by monogenetic volcanoes that formed during single eruptive episodes. The magma supply rate in these volcanic fields is typically low and conduits are not maintained between individual vents. Volcanic fields are volumetrically dominated by mafic magma compositions producing basalts (45-52 wt% SiO_2) and basaltic andesites (52-57 wt% SiO_2). Well-known examples of basaltic volcanic fields include the Eifel volcanic field (Germany) and the San Francisco and San Rafael volcanic fields in the western USA.

The Armenian volcanic highlands follow broadly NW-SE (Gegham, Syunik) and W-E (Vardenis) oriented trends, likely related to regional subsurface geological structures and crustal stress orientations. Some of the monogenetic centres are located in pull-apart basins, regions of localised extension related to the sidestepping of strike-slip faults. In contrast, the monogenetic cinder cones of the Shamiram Plateau represent a volcanic field on the flank of a large shield volcano (Aragats) and are thus independent of regional fault tectonics.

Although largely dominated by mafic and intermediate volcanic products, silicic lava flows and/or pyroclastic deposits occur in all of Armenia's volcanic highlands. Several volcanic vents have produced obsidian flows of rhyolitic composition, including the Arteni complex in the south-western part of Aragats (1.4 – 1.1 Ma), Gutansar (0.31 – 0.24 Ma), Hatis, Spitaksar and Gehghasar in Gegham and various sources in the Vardenis (Khorapor, Kecheldag) and Syunik (Satanakar, Sevkar, Bazenk) volcanic highlands. The most recent obsidian flows in Armenia derive from the volcanic domes of Spitaksar and Geghasar in the southern Gegham volcanic highland. They were dated to between 120 000 and 40 000 years ago. Tools sourced from various obsidian flows in different regions of Armenia were found in archaeological sites from the Middle Palaeolithic (~300-30 ka) to the Early Iron Age (ca. 1100 years BC). Their study was used to characterise the diversity of sources of supply, regional distribution and methods of acquisition of this natural resource through time. Just as the recent find of the oldest leather shoe in the world (ca. 5500 years old), the obsidian artefacts evidence the long history of human activities in Armenia and highlight the role of Armenian obsidian as source of raw material for trade and exchange in prehistoric times as it was found in archaeological excavations quite far from their geological sources.

Straddling the boundary between the Neogene and the Quaternary, Late Pliocene to Early Pleistocene basaltic volcanism is widespread in the Lesser Caucasus. Basaltic lavas (3.25-2.05 Ma) outcrop in the Lori Plateau (northern Armenia), the Javakheti Plateau (northern Armenia & Georgia) and the Kars-Erzurum Plateau (eastern Anatolia, Turkey). Very similar basaltic lavas were also erupted near Yerevan in the Hrazdan River canyon and in the Gegham volcanic highlands. Lava flows from these locations were dated to only ~0.15 to 0.17 Ma. The basaltic lavas form 200-400 thick sequences and include basal pillow lavas and hyaloclastites overlain by pahoehoe flows, often with columnar jointing. The lavas were very hot and fluid and most likely fed from multiple fissures. Due to the similarity of these geological features to those of continental flood basalt (CFB) provinces, the basaltic sequences are considered as a

CFB province. Their size of ~15,000 km^2 areal extent with an erupted volume of ~2250 km^3 makes this basaltic province in the Lesser Caucasus the smallest and youngest CFB in the world. The lavas were erupted due to localised extensional tectonics within an overall setting of continental convergence between the Arabian and Eurasian plates.

Young manifestations of volcanism in Armenia associated with thermal springs are considered as promising sources of geothermal energy and require further investigation. An international consortium headed by Dr. Sci. Arkady Karakhanyan (Institute of Geological Sciences, Armenia) carried out a detailed geophysical and volcanological study of one of those areas, which was followed by recent exploration drilling near the Karkar Holocene volcanic field with financial support of the World Bank.

Seismic and volcanic hazards in Armenia

When an earthquake with a magnitude of 6.9 shook north-western Armenia on December 7, 1988, Armenia became the focus of worldwide attention in the most tragic of circumstances. The so-called Spitak earthquake, named after the town of Spitak, killed over 25000 people and left more than a million Armenians homeless. The cities of Gyumri (formerly Leninakan), Spitak and Vanadzor (formerly Kirovakan) were particularly affected by the devastations. The length of the seismogenic surface rupture is 37 km. The occurrence of the Spitak earthquake was related to movements along the northern segment of the active Garni fault, near the junction with the Pambak-Sevan-Syunik fault. This fault system is the largest active fault system in Armenia with a length of about 400 km.

Evidence for past seismic activity in the Spitak region includes uplifted terraces in the block north of the Pambak-Sevan fault and subsiding areas south of it. There are also a number of strong historical earthquakes in the last few centuries (1319, 1679, 1827, 1840, 1926, 1931 1988 and others) recorded in Armenia. Their occurrence with magnitudes ranging from 6 to 7 provide evidence for the compressive tectonic forces acting on Armenia, related to the present-day northward movement of the Arabian plate at 15-20 mm per year.

The devastation of the Spitak earthquake was the result of a severe underestimation of the magnitude and frequency of seismic hazards, both for the Spitak area and for Armenia and the Caucasus as a whole. Such inadequate hazard assessments and lack of detailed seismological studies contributed to general unpreparedness and a high numbers of casualties. The Spitak earthquake has become a tragic lesson for Armenia but also an impetus for modern studies on active tectonics, seismotectonics and paleoseismology in the country. As a result of these studies, almost 30 years later, Armenia got a new state of the art probabilistic seismic hazard map based on an instrumental seismic catalogue by the Institute of Geological Sciences, a regional survey for seismic protection of the Armenian Ministry of Emergency Situations, comprehensive seismotectonic models, paleoseismology, archeoseismology and an updated historic seismicity database. The seismic hazard map was prepared by a consortium headed by Dr. Sci. Arkady Karakhanyan with involvement of AIR Worldwide (USA), the Global Earthquake Model (GEM) Foundation (Italy) and the Georisk scientific research company (Armenia), with support of the World Bank.

With the seismic hazard being a constant threat, the volcanic hazards in Armenia appear to be less threatening and have fallen under the radar. Despite that, the evidence for both Holocene and historical activity shows that keeping a close watch on Armenia's volcanoes remains important. One of the most spectacular examples of historical volcanic activity is the lava flow from Porak volcano in the Vardenis volcanic highland (Fig. 4). Here, two major basaltic andesite lava flows travelled >20 km towards Lake Sevan in the north. The extremely fresh lava also forms a peninsula into Lake Al-Lich (Fig. 4). Other areas of young volcanic activity include the Karkar monogenetic field further south (Syunik volcanic highland), with 5 generations of Holocene lava flows (9000-6000 ka), and Smbatasar volcano that is even younger. Many of these Holocene volcanoes are located in remote areas that are sparsely populated and without any major infrastructure in their direct vicinity, such that the volcanic risk is relatively low.

Potential volcanic hazards associated with the Aragats volcanic complex are very diverse and include ash and pumice fall, pyroclastic density currents, lava flows and formation of monogenetic cinders cones. The latter hazard is particularly evident for the Armenia Nuclear Power Plant (ANPP), which is located adjacent to a group of Quaternary cinder cones (637-961 ka) in the Shamiram volcanic field (Fig. 4), just 36 km west of Yerevan with its population of ~1.1 million. The ANPP produces currently some 40% of Armenia's electricity. It did not experience any damage in the 1988 Spitak earthquake, but was closed in the aftermath of the event due to vulnerability and other concerns. The ANPP was reopened in 1995, which resulted in major improvements in Armenian power supply.

The ANPP is of enormous political significance: The country is isolated from its neighbours and closed off from other sources of energy because Azerbaijan to the east and Turkey to the west have closed their borders with Armenia, cutting off most routes for oil and natural gas – a blockade that remains in place to this day. Plans to construct a new nuclear power plant are currently under way within the Armenian government.

From a volcanological perspective, the monogenetic nature of the Shamiram cinder cones (Fig. 4) precludes involvement of a long-lived shallow basaltic magma reservoir. However, rates of volcanism in volcanic fields typically wax and wane over long periods, and the monogenetic activity can potentially last over periods of hundreds of thousands to millions of years, such that a flare-up of new eruptions is not impossible. That said, it is unlikely given the volcanic quiescence of the last 600 thousand years.

An international team of scientists conducted a detailed volcanic hazard assessment of the Armenian NPP according to a specific safety guide from the International Atomic Energy Agency (IAEA). Subsequently, the Armenian case study was used in an official IAEA publication (IAEA-TECDOC-1795, 2016) and is nowadays widely utilised as an exemplary study for assessing volcanic and seismic hazards for nuclear installations. Volcanic hazards are an issue for nuclear installations in many countries, mostly in SE Asia and North America.

Geochemical constraints on the petrogenesis of the magmatic rocks

The wide compositional range observed in the volcanic rocks from Armenia makes them amenable to the study of their magmatic evolution. Two key geochemical features are present throughout the various volcanic regions of Armenia (Fig. 5). First, there is no major variation between the Sr and Nd isotope compositions of mafic rocks (basalts and basaltic andesites) compared to more evolved rocks (trachytes and dacites). This pattern (Fig. 5a) suggests that crustal assimilation is negligible because any addition of crustal material to mantle-derived magmas should alter the isotopic ratios. Secondly, all rocks are characterized by negative Nb-Ta anomalies and an enrichment in large ion lithophile elements (Cs, Rb, Ba) and light rare earth elements (La, Ce, Nd) in mantle-normalized trace element diagrams (Fig. 5b), features that are characteristic of active oceanic and continental volcanic arcs. In Armenia, they are best explained as an inherited feature from subduction of the Tethyan Ocean prior to the collisional events.

The volcanic regions of Armenia, from Syunik in the SE via Vardenis and Gegham to Shirak/Lori in the NW can be used as an excellent geochemical recorder of the variations in crustal and mantle structures at depth. Geophysical data indicate that the thickness of the lithosphere increases from the west, underneath Eastern Anatolia (~60 km), towards the east in NW Iran (>200 km). These major structural changes are reflected in the geochemical, isotopic and petrological characteristics preserved in the volcanic rocks. The thicker lithospheric root in the SE of Armenia contributes to a general enrichment in incompatible trace elements and more radiogenic $^{87}Sr/^{86}Sr$ isotope compositions in the Syunik volcanic rocks compared to those in the NW. These geochemical characteristics are due to lower degrees of melting at greater depths and a more enriched melt source composition in the SE. Melting of the subduction-modified components within the lithospheric mantle may have been aided by the removal of the lowermost lithosphere and replacement by convecting asthenosphere, a process that appears to persist for millions of years.

Figures:

Fig. 1: Geographic and geologic overview of Armenia.

a. Location of Armenia in the Lesser Caucasus. NK = Nagorno-Karabakh.

b. Simplified geological map of Armenia. Note the predominance of Oligocene to Quaternary volcanic rocks, which include the four major volcanic regions (Syunik, Vardenis, Gegham, Shirak/Lori) in Armenia.

Fig. 2:

a. Little Ararat and Greater Ararat towering over Yerevan. The building in front of Greater Ararat is part of the Ararat company that produces the famous Armenian cognac. British Prime Minister Winston Churchill was served Armenian cognac at the Yalta Conference in 1945 and he was so impressed that allegedly Armenian cognac was sent to him every year to his London residence until his death in 1965.

b. National Academy of Sciences of Armenia in Yerevan, built from volcanic tuff.

Fig. 3: Aragats volcano.

a. Aragats seen from the Shamiram Plateau around 30 km south of the summit. Note the gentle slope of the volcanic edifice. The small cones and ridges in the foreground are part of the group of monogenetic cinder cones of the Shamiram Plateau.

b. The north summit of Aragats (4090 m) seen from the west summit (3995 m). Note the yellow to orange colours on the lower slope indicating past fumarolic activity and hydrothermal alteration.

c. Massive pumice fall deposit produced by Irind volcano on the south-western slope of Aragats. This Plinian fall deposit demonstrates that Aragats and its subsidiary vents were capable of large explosive eruptions. Note the upward increase in grain size in the Plinian fallout deposit. This single fallout unit is capped by a pyroclastic flow that is vitrophyric in some sections. The increase in grain size and transition to pyroclastic flow are attributed to vent widening and subsequent column collapse.

Fig. 4: Volcanic hazards in Armenia.

a. Porak volcano in the Vardenis volcanic region. Eruptions from Porak have been linked to a historical battle around 778 BC.

b. Lava flow from Porak into the adjacent Lake Al-Lich, forming a prominent peninsula.

c. The Armenian National Power Plant (ANPP) at Metsamor with cinder cones of the Shamiram Plateau in close proximity.

d. Pyroclastic flow deposit in the Vardenis volcanic region. The inset shows a close-up of the deposit (coin for scale).

Fig. 5: Geochemical characteristics of igneous rocks from Armenia.

a. Diagram showing the Sr isotopic composition versus SiO_2 content for igneous rocks from Armenia. The rock suites show horizontal trends, indicating that their petrogenesis was dominated by fractional crystallization without any significant assimilation of crustal material. Sr isotope ratios for the Tezhsar Alkaline Complex were recalculated to the emplacement age of 41 Ma.

b. Trace element concentration diagram normalized to N-MORB for representative samples from the four main volcanic regions in Armenia (Syunik, Vardenis, Gegham, Shirak/Lori). Note the spiky pattern with prominent negative Nb-Ta and Ti anomalies, which are characteristic for volcanic rocks from subduction zones. Abundances of highly incompatible trace elements are systematically decreasing from the SE (Syunik) to the NW (Shirak/Lori), indicating a contribution from a thicker mantle lithosphere in the SE.

Acknowledgements:

This paper is dedicated to the memory of Dr. Sci. Arkady Karakhanian (1951-2017), famous Armenian geologist, founder and director of the Georisk Scientific research company (1998-2005), and director of the Institute of Geological Sciences of the Armenian National Academy of Sciences between 2006 and 2017. He has made great contributions to geological, geoarchaeological and seismological studies in Armenia and other countries and is the founder of a school of active tectonics, paleo- and archaeoseismology in Armenia. A new seismotectonic model of Armenia created under his leadership, which included assessments of the risk of segments of active faults, became the basis for a new seismic zoning map adopted by the government of Armenia and used for safe construction of important buildings in the Republic of Armenia. We thank the team from the Institute of Geological Sciences of the Armenian National Academy of Science for logistical support during fieldwork and editor Ralf Gertisser for helpful advice and encouragement to write this article.

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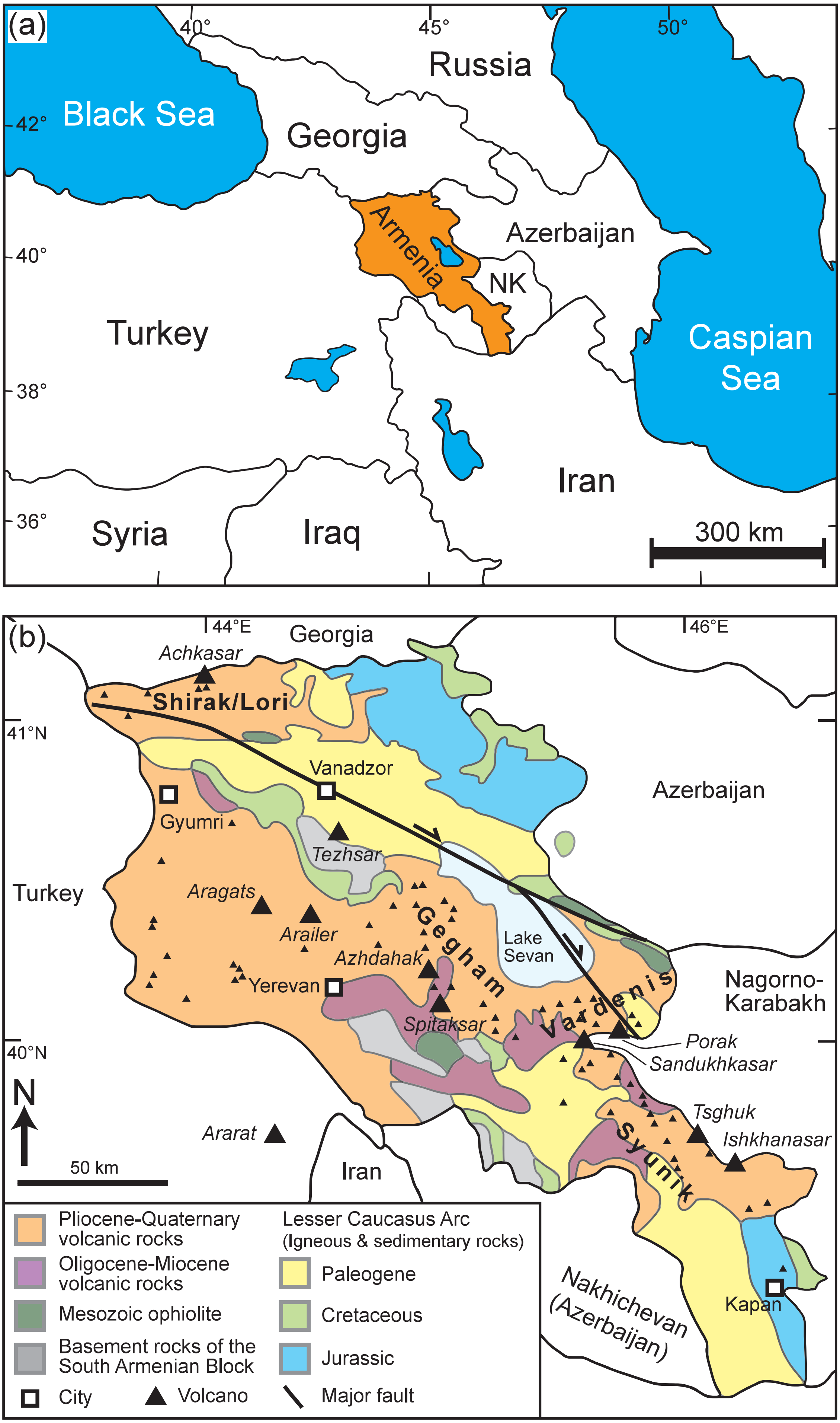
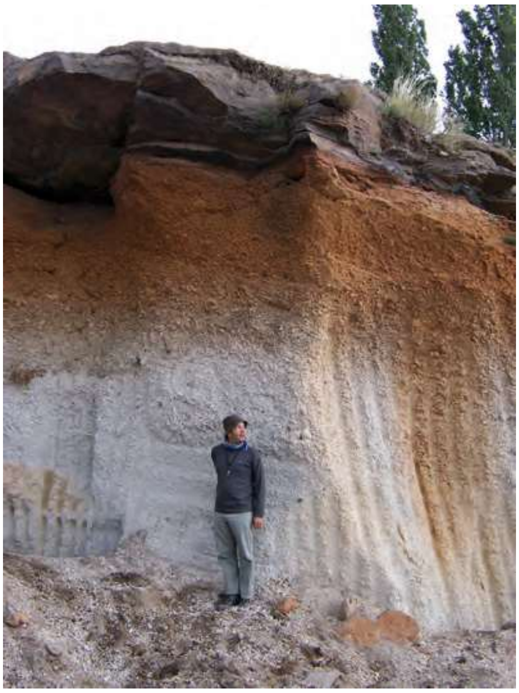
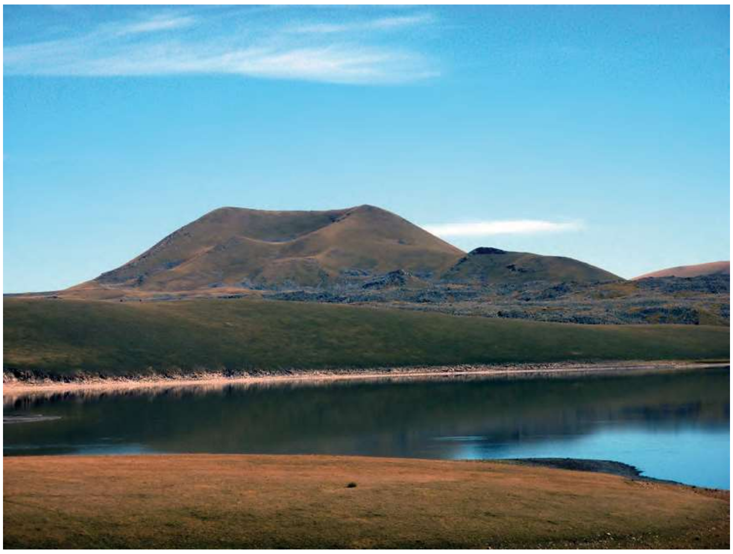
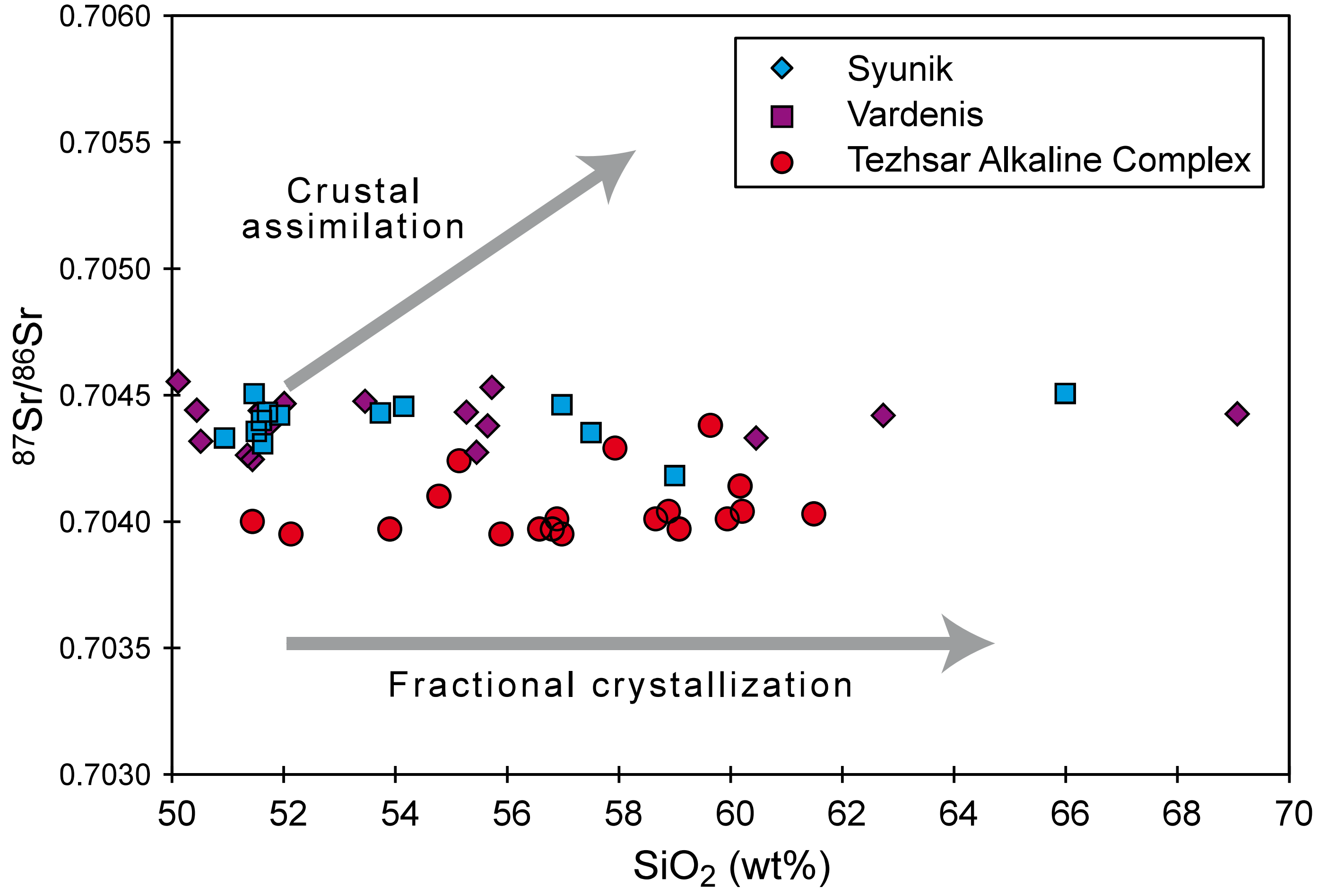


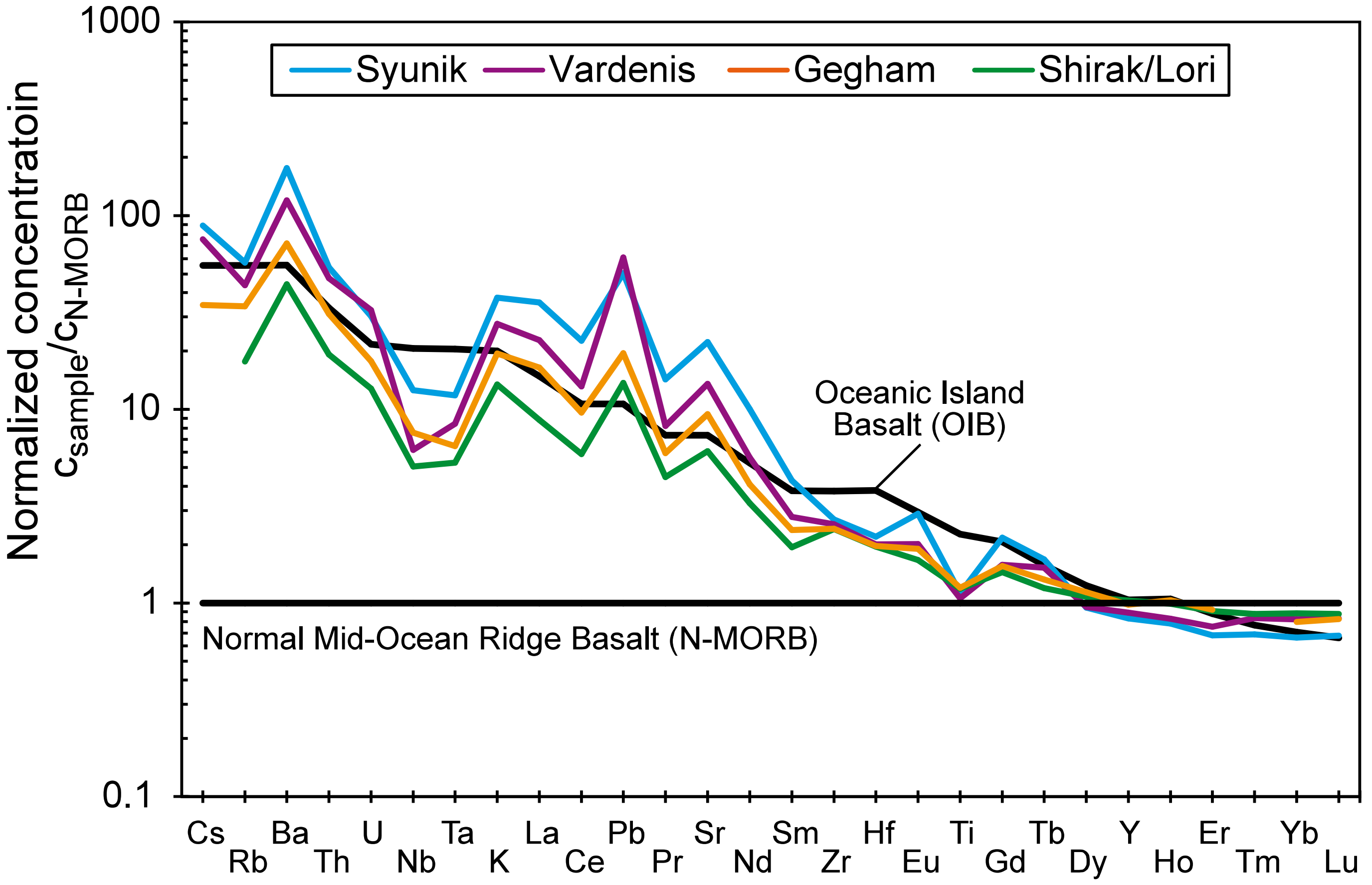
(a)
Black Sea
Russia
Georgia
Armenia
Azerbaijan
NK
Turkey
Caspian Sea
Iran
Syria
Iraq
300 km
40°
45°
50°
42°
40°
38°
36°
(b)
44°E
46°E
41°N
40°N
Georgia
Achkasar
Shirak/Lori
Vanadzor
Azerbaijan
Gyumri
Tezhsar
Turkey
Aragats
Arailer
Azhdahak
Gegham
Lake Sevan
Yerevan
Spitaksar
Vardenis
Porak
Sandukhkasar
Nagorno-Karabakh
Tsghuk
Ishkhanasar
Syunik
Ararat
Iran
N
50 km
Kapan
Nakhichevan (Azerbaijan)
Pliocene-Quaternary volcanic rocks
Oligocene-Miocene volcanic rocks
Mesozoic ophiolite
Basement rocks of the South Armenian Block
City
Volcano
Lesser Caucasus Arc (Igneous & sedimentary rocks)
Paleogene
Cretaceous
Jurassic
Major fault







Syunik
Vardenis
Tezhsar Alkaline Complex
Crustal assimilation
Fractional crystallization
0.7060
0.7055
0.7050
0.7045
0.7040
0.7035
0.7030
87Sr/86Sr
50
52
54
56
58
60
62
64
66
68
70
SiO2 (wt%)



Syunik
Vardenis
Gegham
Shirak/Lori
Oceanic Island Basalt (OIB)
Normal Mid-Ocean Ridge Basalt (N-MORB)
Normalized concentratoin
csample/cN-MORB
1000
100
10
1
0.1
Cs
Rb
Ba
Th
U
Nb
Ta
K
La
Ce
Pb
Pr
Sr
Nd
Sm
Zr
Hf
Eu
Ti
Gd
Tb
Dy
Y
Ho
Er
Tm
Yb
Lu