Relationship of late Quaternary tectonics and volcanism in the Khanarassar active fault zone, the Armenian Upland

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ABSTRACT

The Syunik rhombus-like structure in the Khanarassar active dextral fault zone of Armenia is a typical pull-apart basin, formed between terminal parts of two adjacent *en echelon* fault segments. Some component of subsidence associated with the faults of the structure is found between the *en echelon* segments; nevertheless, the dextral component continues to be predominant even on the boundaries of the pull-apart basin. The late Pleistocene and Holocene lava volcanoes of the basin are also associated with those faults that have a component of extension. The relative ages of fault displacements and volcanic eruptions have been identified by the mutual correlation of lavas, moraines and topographic features and by archaeological and radiocarbon dating. According to the interpretation of rupturing and volcanism, major earthquakes and volcanic eruptions appear inter-related and three pulses of such activity during the earlier and middle Holocene have been identified.

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Introduction

The relationship between tectonic activity and volcanism is accepted in general, but its specific structural and chronological manifestations in regions of recent continental collision are versatile and not satisfactorily investigated or understood. The study region is a part of the Khanarassar fault zone, which, in turn, continues the Pambak-Sevan fault and comprises a component of the North Armenian active fault arc convex northwards (Fig. 1). The arc is the main structural manifestation of the recent collision between the Arabian and Eurasian plates within the Armenian Upland region. The faults of the arc dip steeply and are characterized by oblique, largely strike-slip displacements. The external (NW and NE) sides of the faults are as a rule uplifted. The strike-slip component is sinistral in the northwestern and dextral in the northeastern segments of the arc. The Khanarassar fault forms the greater part of the northeastern arc segment. The average rate of late Quaternary dextral motion is estimated as 4–5 mm yr^{-1} (Trifonov *et al.*, 1994), while the reverse component of motion is 10–20 times less than this. A major peculiarity of the Khanarassar fault is the Holocene volcanism in its zone. The volcanism is manifested most completely in the part of the fault considered below, located in the highest ($\approx$ 3000 m above sea level) part of the Syunik volcanic upland, previously poorly studied because of its inaccessibility. One of the authors visited the region (Fig. 1) in 1967–68 (Mkrtchian *et al.*, 1969); more detailed studies were carried out in 1993 and 1994, and these have served as a basis for the present paper.

Young geological formations; archaeological dating

Volcanic rocks of Middle Eocene, Neogene, Lower and Middle Pleistocene have provided substrata for late Pleistocene and Holocene tectonovolcanic events (Table 1). The Middle Eocene is represented by andesitic-basaltic porphyrites, and the Neogene is represented by rhyolite-dacites, that are partly overlain by basaltic and andesitic-basaltic lava flows of the Lower and Middle Pleistocene. The lava surface is essentially eroded and often covered with a layer of a soil. The individual flows cannot be differentiated. Several tephra or lava cones corresponding to semi-ruined Lower and Middle Pleistocene volcanoes have been identified. The largest is the Karkar volcano.

The late Pleistocene basaltic and andesitic-basaltic lava flows differ from the Lower and the Middle Pleistocene, since their features are essentially less eroded. It is possible to differentiate these flows on the aerial photos and at the locality. The tephra cones with semi-eroded craters have been well preserved. The Late Pleistocene valley glaciation moraines are distinct, being composed of local volcanic material and do not exceed several kilometres in length. The similarity in the preserved details of moraine topography suggests that all the identified moraines are approximately synchronous. They overlie the late Pleistocene (or older) volcanic landforms (point 1 in Fig. 1), and we consider that they date from the end of the late Pleistocene.

The Holocene andesitic-basaltic volcanoes and lava flows can be differentiated into three generations. The lavas of the first (oldest) generation are exposed only in the western and the eastern parts of the Holocene lava field, are seen to cover the late Pleistocene moraine at the eastern shore of the Khaitalich Lake (2 in Fig. 1). The second generation lavas and volcanoes form the northern part of the Holocene lava field where the lava surface is only partially eroded. The surface of lavas of the third generation, forming the central part of the Holocene lava field, is not at all eroded. Lavas of the second and the third generations have retained practically all features of the initial volcanic landscape. The slopes of some of the Holocene volcanoes are composed of tephra in addition to lavas.

Apart from lavas and tephra the Holocene deposits include alluvium in small watercourses and loams and sandy loams of recent lakes that commonly dry up in summer. The deposits are enriched with local volcanic rock debris. The recent channels are as a rule incised for no more than 1 m into the flat valley bottoms. The Holocene and late Pleistocene lava flows have, to a great extent, followed the largest valleys, which thus had originated not later than in the late Pleistocene. The two small, low river and ravine terraces are of late Pleistocene age. The relationship between offsets on faults and these river and lava flows apparent in the geomorphology aids in dating fault movements.

Archaeological remains provide the possibility for more detailed dating of the Holocene volcanic eruptions and thus tectonic movements. The boulders of the Pleistocene lava within all the region and particularly around the southern part of the Holocene lava field are covered with numerous petroglyphs created with stone tools (Karakhanian and Safian, 1970) (Fig. 2). Petroglyphs have been revealed at the boulders of the first generation Holocene lavas, but they are missing from the second and the third generation lavas (Mkrtchian *et al.*, 1969). An immediate covering of a boulder with petroglyph by third generation lavas was found at the southern margin of the Holocene lava field (3 in Fig. 1). Thus, the petroglyphs appear younger than lavas of the first generation and older than lavas of the second and third generations.

Archaeologists have dated the petroglyphs at 7000 to 3000 (perhaps 2000) yr BC (Karakhanian and Safian, 1970). It is possible to narrow this time interval by an analysis of the petroglyph themes and some historical correlations. Although some petroglyphs were probably made in the Earlier Neolithic, the themes and the stylistic unity lead us to the conclusion that a large majority of the petroglyphs were a product of a later culture (Karakhanian and Safian, 1970), of cattle-breeders and hunters that lived on the Armenian Upland. The images of vehicle wheels of two types: solid and with spokes, and manifestations of horse-breeding first signs of proto-Hittite penetration into Anatolia have been dated at the end of the 4th or the beginning of the 3rd millennia BC (Hrozny, 1938). It is deduced therefore that the petroglyphs were created in this period. The lavas of the second and third generations should therefore be younger (see above).

The upper age limit of the eruption of the third Holocene generation lavas was dated by the investigation of an old burial mound situated near the northern margin of the southwestern lava flow of the third generation (4 in Fig. 1) where boulders of this lava were used for mound building. Before trenching, the mound was 8–9 m in diameter and 60 cm high. A lens of filled loam up to 40 cm was found after excavation of the upper stones (30–40 cm). The lower

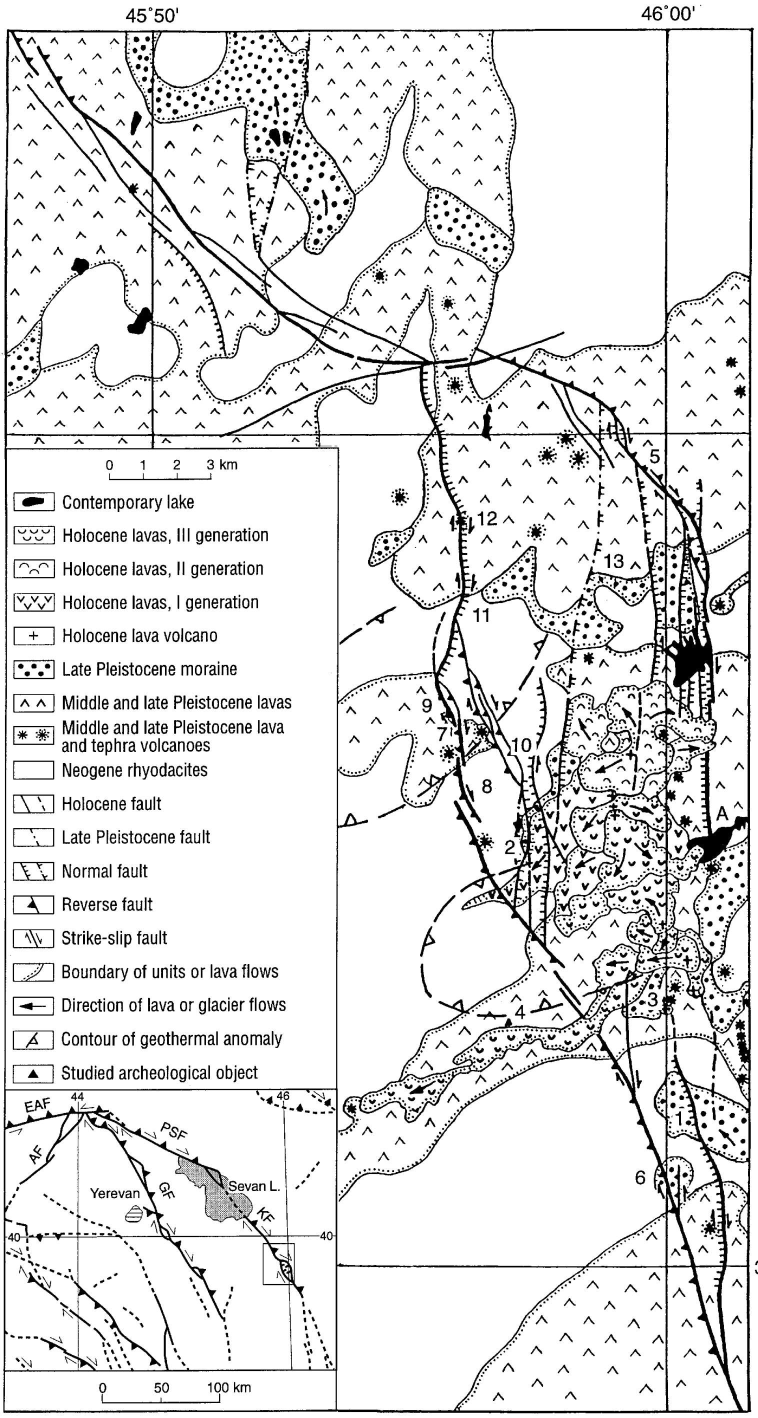

Fig. 1 Structural geological map of the Syunik pull-apart basin in the Syunik Upland, Armenia. The main faults are marked by thick lines and the supposed faults are marked by interrupted lines. Hachures on normal faults are directed to the subsided side, and triangles on reverse faults are directed to the uplifted side. Oblique faults are shown as a combination of normal (or reverse) and strike-slip faults. Points on formation or lava flow boundaries are shown on the younger formation. A, the Agnalich (Allah-li) Lake; K, the Karaghel Lake. Numerals on the map are explained in the text. A contour of the region is shown in the insert representing active fault of the Armenian Upland (Trifonov *et al.*, 1994). AF, the Akhurian fault; EAF, the East Anatolian fault zone; GF, the Garni fault; KF, the Khanarassar fault; PSF, the Pambak-Sevan fault.

30 cm-thick layer of stones and filled ground and the Pleistocene volcanic basement underlay the lens. Obsidian tools of the Neolithic style – small pieces of charcoal, rare pieces of bones and grey modelled ceramics – were found in the lens. The radiocarbon sample of the loam, collected from the lens at a depth of 45–65 cm gave a date of 4720 ± 140 years. Thus, it appears that the lavas of the second and third generations were both erupted around the beginning of the 3rd millennium BC. Because of the different level of erosion of the features, we assume that the third generation is younger than the second generation, perhaps by a few centuries.

Active faults

The Khanarassar fault zone changes its configuration from NW to SE within the investigated region (see Fig. 1) in which there is a N–S elongated rhombus-like structure with two NW-trending and two N-trending sides.

The fault that marks the northeastern boundary of the rhombus-like structure is characterized by relative uplift of the northeastern side as in the farther northwestern segments of the zone. The vertical offset ranges up to 5 m at the surface of the middle Pleistocene lavas and decreases down to 2–3 m to the south-east at the younger land forms. The late Pleistocene slopes of the valley are offset 60–70 m dextrally, 3 km southeastwards of the Uchtepe mountain (5 in Fig. 1). The Holocene channel of the valley is offset 5–6 m dextrally and uplifted in the northeastern side 0.3 m.

The southwestern boundary of the rhombus-like structure consists of several *en echelon* fault segments characterized by relative uplift of the southwestern sides. An isolated small valley is offset 20–30 m dextrally, 1 km to the north-west of the Navassad mountain (6 in Fig. 1). This fault bears evidence of renewed displacement and dammed a small basin, in which in a 1 m pit we discovered a 10 cm loam layer (beneath 15 cm of modern soil) enriched with organic material radiocarbon dated to 2020 ± 160 yr. A 30 cm-thick layer of brown loam with rare stones and discrete Neolithic obsidian tools lies below, beneath which there is a > 45 cm-thick layer of plastic clay, which we believe corresponds to deposition associated with earlier fault displacement (one or two strong earthquakes?). A sample from the lower 10 cm of the clay layer gave a radiocarbon age of 5000 ± 160 yr. All of the identified Holocene fault displacements appear to have occurred after the petroglyphs had been carved. Thus, the subsidence of the basin by 1–2 m took place during approximately the last 5000 years.

The same fault segment offsets a valley dextrally by 180–200 m 2.5 km to the north-west. The valley is bounded on its northern side by the late Pleistocene lava flow and filled upstream with a late Pleistocene moraine. The offset therefore represents movement during the latest part of the late Pleistocene and the Holocene. The average rate of strike-slip motion is thus several millimetres per year, coincident with the slip rate in the northern part of the Khanarassar zone. Further to the north-west the fault crosses a third Holocene generation lava flow. The lava flow itself does not show any visible displacement.

Northwestward the investigated fault segment is overstepped *en echelon* by other segments that retain the same structural features. The relative uplift of their southwestern sides reaches 2.5–3 m. The fault planes appear to dip ≈ 50° to the south-west, and have a reverse component of motion. A dextral component is shown by the 3 m offset of the channel of a small creek, which is also uplifted 0.8 m to the west across the fault (7 in Fig. 1). A cattle wall constructed in the 17th or 18th century AD is curved dextrally 30 cm along the other segment (8 in Fig. 1), and suggests an average slip rate of 1–1.5 mm yr^{-1} during the last 200–300 yr, that in the absence of strong earthquakes can be assumed to reflect surface creep. The extreme northwestern segment (9 in Fig. 1) is represented by two parallel scarps 3 m and 4 m high, respectively. Cracks like those formed in the uplifted side of the 1988 Spitak earthquake reverse fault in Northern Armenia, are observed in the fresher 4 m upper scarp. Along-strike this scarp changes to a sequence of short (up to 30 m) *en echelon* extension fissures striking N40–50°E and linked with short ridges striking N300–310°W, typical of strike-slip (dextral) motion.

Four small faults with similar trend stretch eastward at a distance of 0.3–1.5 km, merging with the main fault to the north and the south. They also have uplifted western flanks, and dam-up cross-cutting channels. At the watershed between the channels, at a land surface no younger than late Pleistocene, the height of the scarps is 0.5–2 m, and is combined with the dextral offset of the watershed itself by tens of metres along each of the faults. Eastward of the easternmost fault a rupture with (1 m) uplifted eastern side has been noted (10 in Fig. 1), with the suggestion of a further dextral component of displacement. The fault scarp cuts the surface of the oldest Holocene lavas.

The faults of the southwestern and northeastern boundaries of the pull-apart bend and continue to its western and eastern boundaries, respectively. The western boundary is formed by a normal fault scarp, downthrown east by 5 m at the surface of the pre-late Pleistocene rocks, but much reduced at the late Pleistocene lava surface. The southern margin of the late Pleistocene lava flow, located 6 km to the north of the Karkar mountain (11 in Fig. 1), is offset dextrally 56 m. Further northwards, 2.5 km to the south-west of the Yerablour mountain (12 in Fig. 1), the cone of the middle Pleistocene (?) volcano appears to be offset dextrally by several tens of metres and to have subsided several metres along the eastern side of the fault.

The eastern boundary of the pull-apart is formed by an *en echelon* set of closely related normal fault scarps involving downthrow to the west. The scarp height reaches 10–12 m at the Neogene rock surface, but reduced to 3 m southwards at the surface of the late Pleistocene lavas. Several parallel normal fault scarps with downthrown eastern sides are located to the west of the main fault. The longest western scarp (13 in Fig. 1) is up to 10 m high in the northern part and shows no evidence of Holocene activity. The fault displaces the surface of the late Pleistocene lavas and serves as a western boundary for the spreading second Holocene generation lava flow. Further to the south the fault has apparently experienced some Holocene reactivation since it can be traced as a low scarp cutting the first Holocene generation lava surface.

The space between this fault and the eastern boundary fault represents a graben up to 3.5 km wide. All the Holocene lava volcanoes are confined here. Northwards of the Holocene lava field the graben forms a topographic basin; in the most depressed eastern part of this lies Karaghel Lake (K in Fig. 2) formed due to the damming of the river valley by the eastern boundary fault.

At a distance of up to 1.5 km from the eastern boundary fault the bottom of the graben is ruptured by several normal fault scarps 1–6 m high, with downthrown eastern sides. Narrow troughs, up to 1 m deep and up to 15 m wide, located immediately adjacent to the fault scarps are characteristic of the downthrown sides of these faults. Two smaller normal fault scarps continue to the south and offset second Holocene generation lavas. The river was dammed after the eruption of the late Pleistocene lavas. The valley has been offset dextrally 200–300 m in total during the end of the late Pleistocene and the Holocene: an average slip rate of several millimetres per year.

Segments of the eastern boundary fault can also be mapped to the south of the Holocene lava field. The normal fault scarp height increases N–S from 1–1.5 m to 3 m at the eastern slope of the Navassard mountain (14 in Fig. 1) downthrowing west. Southwards the fault shifts a small dry valley dextrally 5–7 m.

The faults of the eastern and southwestern boundaries merge into a single fault zone in the farthest southern part of the structure. Two small northward-trending faults are identified: one branches off 1 km to the west of the Navassard mountain (6 in Fig. 1) and is traced for 1.5 km, its western side uplifted 2.5 m and displaced dextrally 11 m; the second fault branches off 3 km further to the north and is traced for 2.8 km. A small channel is offset dextrally 3 m. The good geomorphological preservation attests to the relative youth of both ruptures. It seems possible that the second fault offsets even the surface of the third Holocene generation lavas and may be related to the last dated seismic event at 2020 ± 160 yr BP.

Relationship between the active faults and the volcanism

The northeastern and southwestern boundary faults of the rhombus-like Syunik structure are immediate continuations of the adjacent segments of the Khanarassar active fault and are characterized by the same morphological and kinematic parameters. The strike-slip component of motion diminishes southwards on the eastern boundary and decreases northwards along the western boundary fault. The internal faults of the rhombus-like structure, parallel to its western and eastern boundaries, are normal and normal-dextral. Thus, the Syunik structure is a typical pull-apart basin created at the site of *en echelon* overstepping of two strike-slip segments of the Khanarassar fault.

The andesitic-basaltic lava volcanoes of the Holocene and, to a greater extent, late Pleistocene age are arranged inside and on the margins of the rhombus-like structure. The most clearly identified Holocene volcanoes form the N-trending chains along the eastern part of the structure. They are located either on the continuation of normal faults at the eastern margin and inside of the structure, or *en echelon* oversteps of these faults. In the western part of the Syunik structure the N-trending normal-dextral faults and the NW-trending reverse-dextral faults form a smaller rhombus-like structure where strike-slip motion has been taking place under compression. At this location the late Quaternary volcanoes are absent. Thus, the late Quaternary volcanoes of the region are directly related to the extensional faults of the pull-apart basin.

The latest major earthquake, dated in the southern part of the Syunik structure (6 in Fig. 1) at 2020 ± 160 yr BP occurred to the south-east of the structure and was not followed by eruptions. Damage, likely related to the earthquake, has been found in the ancient necropolis near the village of Zorakar, 30 km to the south-east of the Syunik structure. Radiocarbon ages of two destroyed graves are 1600 ± 150 and 1990 ±110 yr. Since that time the Khanarassar zone has been in stable seismic quiescence; it is possible that this points to a strong earthquake in preparation.

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