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Intracanyon basalt lavas of the Debed River (northern Armenia), part of a Pliocene–Pleistocene continental flood basalt province in the South Caucasus

Hetu Sheth [a,*], Khachatur Meliksetian [b], Hripsime Gevorgyan [b], Arsen Israyelyan [b], Gevorg Navasardyan [b]

[a] Department of Earth Sciences, Indian Institute of Technology Bombay, Powai, Mumbai 400076, India
[b] Institute of Geological Sciences, Armenian National Academy of Sciences, 24a Marshal Baghramian Avenue, 0019 Yerevan, Armenia

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ABSTRACT

Late Pliocene to Early Pleistocene (~3.25–2.05 Ma), 200–400 m thick basalt lavas outcrop in the South Caucasus region, including the Kars–Erzurum Plateau (northeastern Turkey), the Javakheti Plateau (Georgia–Armenia), and the Lori Plateau (northern Armenia). These fissure-fed, rapidly erupted fluid lavas filled pre-existing river valleys over many tens of kilometres. The basalts exposed in the Debed River canyon, northern Armenia, are ~200 m thick and of three morphological types: (1) basal pillow basalts and hyaloclastites, overlain by (2) columnar-jointed pahoehoe sheet flows, in turn overlain by (3) slabby pahoehoe and rubbly pahoehoe flows. The lower and middle lavas show evidence for damming of river drainage, like many lavas of the Columbia River flood basalt province, Scotland, Ireland, and Iceland. There is also evidence for syn-volcanic faulting of the early lavas. Related basalts also outcrop in the Gegham Uplands and the Hrazdan River basin in Armenia. This 3.25–2.05 Ma South Caucasus basalt province, covering parts of Turkey, Georgia and Armenia, has an estimated areal extent of ~15,000 km^2 and volume of ~2250 km^3. Because its main geological features are remarkably like those of many continental flood basalt (CFB) provinces, we consider it a true, albeit small, CFB province. It is the smallest and youngest CFB in the world. An analogue closely similar in major features is the Late Miocene Altos de Jalisco CFB province in the western Trans-Mexican Volcanic Belt. Both provinces formed during lithospheric pull-apart and transtensional faulting. Their broader significance is in showing flood basalt size distribution to be a continuum without natural breaks, with implications for geodynamic models.

1. Introduction

The large Turkish–Armenian–Iranian orogenic plateau, defined by the regions of Eastern Anatolia (Turkey), Lesser Caucasus (Armenia, Georgia and Azerbaijan) and northwest Iran (Fig. 1), is a product of the Cenozoic Arabia–Eurasia collision and the closure of the Neo-Tethys Ocean, estimated to have occurred between 35 and 20 Ma (e.g., Keskin, 2007; Allen and Armstrong, 2008 and references therein). Voluminous post-collisional magmatism has occurred on the plateau >500 km from the Bitlis–Zagros suture, from the Late Miocene until the present day, and is mafic to felsic in composition, often with an alkalic character (e.g., Karapetian et al., 2001). The Armenian Highlands, the mountainous region shared by Armenia, Georgia, Turkey and Iran (Fig. 1), represent the former active margin of Eurasia, and the Sevan–Akera ophiolites (Fig. 1) form a 300 km long boundary between the South Armenian Block (a Gondwanan microcontinental fragment containing Proterozoic metamorphic rocks and younger sediments, ophiolites, and subduction-related volcanic rocks) and the Mesozoic-age Lesser Caucasus volcanic arc.

Relatively recent basaltic volcanism is widespread in the South Caucasus region and covers parts of Armenia, Georgia, and Turkey (Figs. 1, 2). Late Pliocene to Early Pleistocene (~3.25–2.05 Ma) basalt lavas (Lebedev et al., 2007), forming sequences 200–400 m thick, are exposed in the canyons of the Debed and Dzoraget Rivers in the Lori Plateau (northern Armenia), in the canyon of the Akhuryan River (Armenia–Turkey), in the adjoining Kars–Erzurum Plateau (northeastern Turkey), and in the Javakheti Plateau (Georgia–Armenia). The same basalts are also found in the Gegham Uplands in central Armenia as well in the Hrazdan River canyon up to the city of Yerevan (Figs. 1, 2).

These widespread basalt lavas have been commonly described as "dolerites" in the existing literature (mostly in the Russian language), owing to their common doleritic, ophitic textures, and have been ascribed to fissure eruptions, like continental flood basalts (Kharazyan, 1966; Ghukasyan, 1970, 1976; Kharazyan, 1983; Jrbashian et al., 1996; Kharazyan, 2012). English-language publications on these basalts are very few. Keskin et al. (1998) briefly mentioned that 3.5–2.7 Ma basalts of the Kars–Erzurum Plateau, well-exposed around Horasan and

* Corresponding author. Tel.: +91 22 25767264, +91 9987094012; fax: +91 22 25767253.
E-mail address: hcsheth@iitb.ac.in (H. Sheth).

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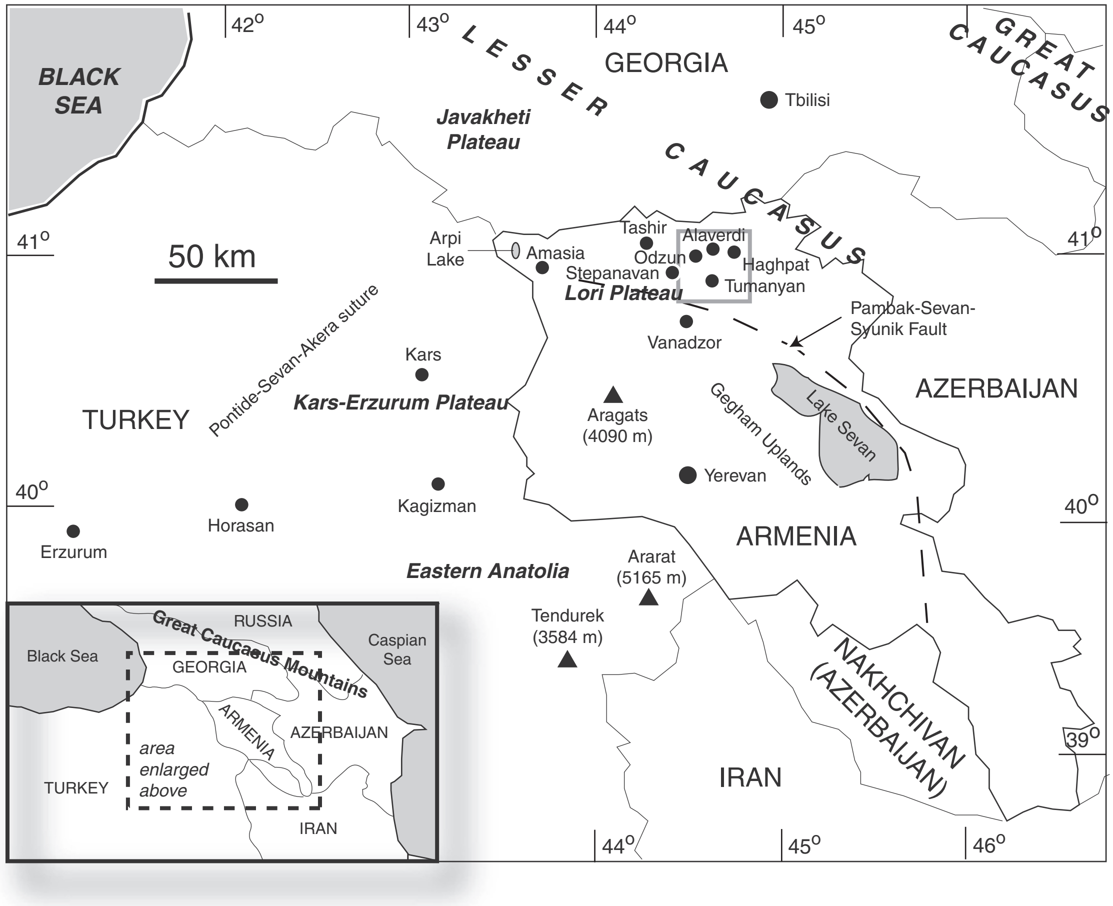

Fig. 1. Map of Armenia and surrounding countries, showing some major topographic and geological features, as well as localities mentioned in the text (filled circles). Some of the major Miocene–Quaternary stratovolcanoes in the region are shown (filled triangles). The box over the northern part of Armenia shows the area of the present study. Based partly on Neill et al. (2013).

Kagizman (Fig. 1), constitute the latest stages of the 11–2.7 Ma collision-related volcanism in this region. Lebedev et al. (2007, 2008a,b) have provided geochemical data and K–Ar ages on the basalts of the Javakheti Plateau and discussed their regional stratigraphic correlations. They state that these lavas flowed along pre-existing river valleys for many tens of kilometres. Geochemical data on their counterparts in northern and northwestern Armenia have been provided by Neill et al. (2013) and Meliksetian et al. (2014). However, there are no recent studies describing the physical volcanology of these widespread basalt lavas. Here we describe and discuss the geological and volcanological features and the eruption environments of basalts exposed in the Debed River canyon in northern Armenia (Fig. 2). We then discuss why the 3.25–2.05 Ma basalt province covering parts of Turkey, Georgia and Armenia (Fig. 2) should be considered a continental flood basalt (CFB) province, and what such a recognition implies for CFB size distribution, our conceptual understanding of CFB volcanism, as well as geodynamic models.

2. Petrography, geochemistry, and petrogenesis

Kharazyan (1966), who described pillow basalts and hyaloclastites of the Debed River canyon near Tumanyan (Fig. 1), provided three major oxide analyses, and Neill et al. (2013) analysed seven samples of these basalts collected from the area between Tashir, Amasia and Arpi Lake (Fig. 1) for major and trace elements and Sr–Nd isotopic ratios. Neill et al. (2013) describe the rocks as sub-ophitic dolerites with rare phenocrysts of plagioclase or clinopyroxene, the latter commonly rimmed or replaced by amphibole. Ten analysed samples are low-MgO (4.7–6.9 wt.%) basalts with little isotopic evidence for crustal contamination. The SINCLAS norm calculation program of Verma et al. (2002) shows that, of the ten samples, four are basaltic trachyandesites (mugearite), three are trachybasalts (hawaiites), and one is a subalkalic basalt, whereas two are classified as alkali basalts (the pillow basalt and hyaloclastite of Kharazyan, 1966). The seven samples of Neill et al. (2013) have normative hypersthene (1.6–12.3 wt.%). Meliksetian et al. (2014) state that these "plateau basalts" are mostly medium-K basalts, trachybasalts and basaltic trachyandesites, with a narrow silica range ($SiO_2 = 48–53$ wt.%) and low MgO (<7 wt.%). Their trace element and Sr–Nd isotopic data suggest ≤10% melting of a mantle source which was moderately enriched by Mesozoic Tethyan subduction input. The Sr–Nd isotopic ratios ($^{87/86}Sr = 0.7041–0.7045$, $^{143/144}Nd = 0.5128–0.5129$ and $\varepsilon_{Nd} = +3$ to $+5$) are homogeneous and among the most "depleted" (mantle-like) in magmatic rocks of the Turkish–Armenian–Iranian Plateau, indicating negligible crustal contamination. Neill et al. (2013) propose that the trigger for this plateau basalt magmatism some 25 million years after the initial Arabia–Eurasia collision may be small-scale lithospheric mantle delamination and lower lithospheric heating, during asthenospheric upwelling following the break-off of the Tethyan slab.

3. Morphological features of the Debed River flood basalts: field observations and interpretations

The Debed River flood basalts are ~200 metres thick and form flat-topped plateaus with the stepped, "trap" landscape (Fig. 3a, b), typical of continental flood basalt (CFB) provinces like the Deccan or the

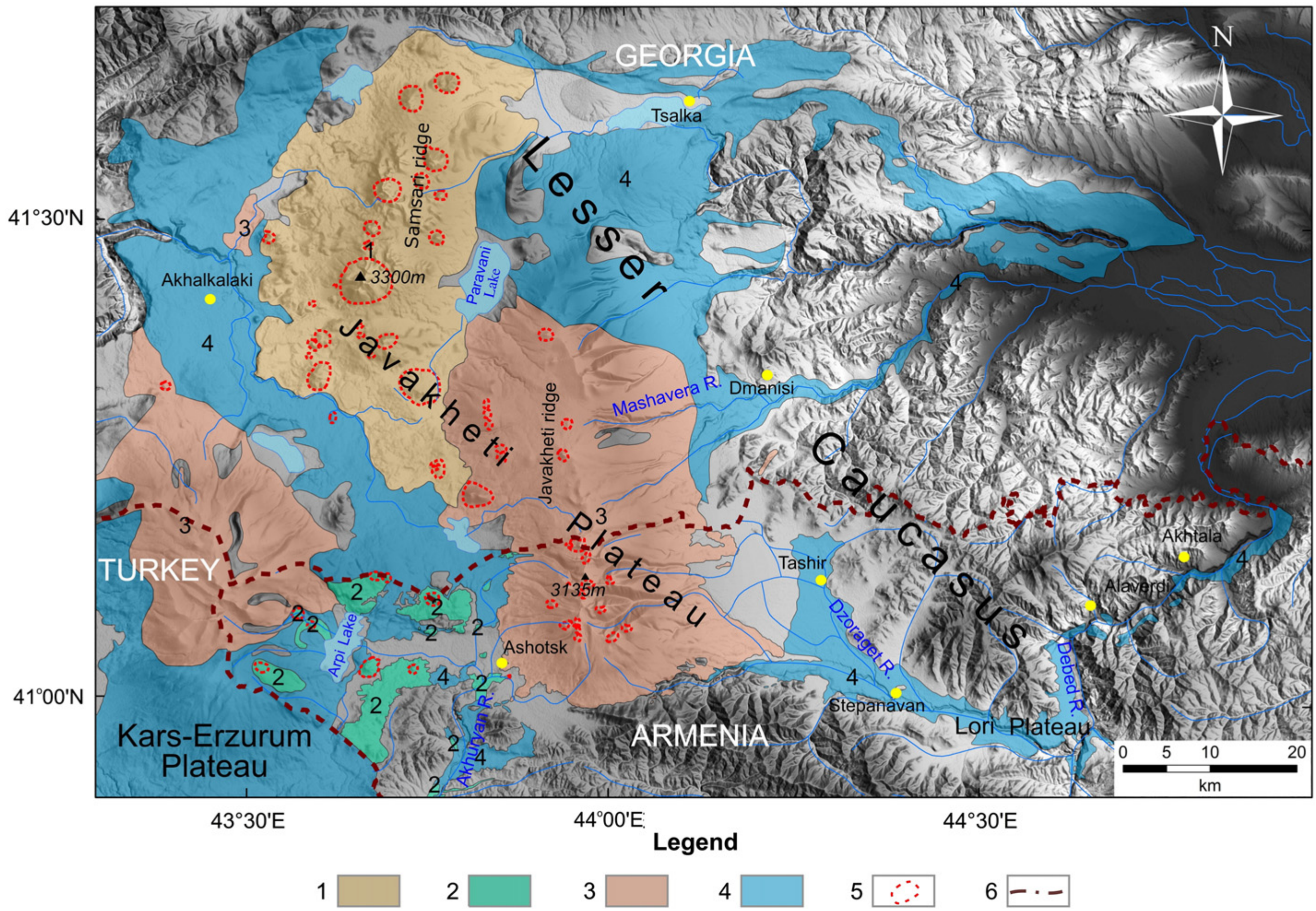

Fig. 2. Geological map of northeastern Turkey, southern Georgia and northern Armenia, showing the South Caucasus basalt province (blue). The modern rivers are shown in darker blue. Key to legend: (1) Upper Pleistocene – Holocene Samsari Ridge – andesites, dacites. (2) Lower-Middle Pleistocene volcanic centres of the southwestern periphery of Javakheti Ridge (the Cone series of Neill et al., 2013): hornblende andesites, dacites, trachyandesites, and trachyandesites. (3) Lower Pleistocene Javakheti Ridge Series: trachyandesites, dacites. (4) Upper Pliocene to Lower Pleistocene doleritic basalts and basaltic andesites (the Valley series of Neill et al., 2013 and the CFB described in this paper). (5) Volcanic centres. (6) Country borders. Map is based on Skhirtladze (1958), Erentoz (1961), Adamia (2004), and Kharazyan (2005).

Columbia River. However, the top of the Debed canyon basalts stands hundreds of metres lower than the surrounding mountains composed of Upper Jurassic to Lower Cretaceous island arc rocks. Thus the Debed River basalts are intracanyon lava flows which flowed along pre-existing river valleys and filled them partly, with a level top (Fig. 3a, b). They thus closely resemble the 16.7–16.0 Ma, intracanyon, Imnaha Formation basalts of the Columbia River CFB province (Reidel et al., 2013).

The Debed River basalts are of three morphological types: (1) pillow basalts at the base of the sequence (with subordinate hyaloclastites), grading upwards into (2) columnar-jointed pahoehoe sheet flows, in turn overlain by (3) slabby pahoehoe and rubbly pahoehoe flows.

3.1. Pillow lavas

Good exposures of the pillow basalts are found around Tumanyan railway station and for several kilometres south and north of it along the Yerevan–Alaverdi road (Figs. 4, 5). Just south of the Tumanyan station a 25 m high cliff beside the railway track exposes well-formed, closely packed basalt pillows with a hyaloclastite horizon (containing some pillow fragments) near the base (Fig. 4a, b). The pillows are up to 1 m in size and show characteristic features such as convex-upward shapes and lateral connections and radial cracks. Other exposures near Tumanyan show that some of the pillow lavas are in direct lateral juxtaposition with thick, tabular, columnar-jointed pahoehoe sheet flows (Fig. 5a). In other exposures, the pillow basalts are seen forming the lower parts of pahoehoe sheet flows tens of metres thick (Fig. 5b, c).

3.2. Interpretation

Kharazyan (1966) interpreted the pillow basalts and hyaloclastites of the Debed River canyon as indicating the entry of basaltic lavas into river valleys, supported by his observations of locally interlayered lacustrine and fluviatile sediments. The widespread pillow lavas indicate that the earliest eruptions were subaqueous, effusive, and low-eruption rate (Batiza and White, 2000). The hyaloclastites may indicate local quench fragmentation of lava entering cold water, presumably at shallow water depths (Batiza and White, 2000). Alternatively, the hyaloclastites may represent the mechanical plucking of fresh lava from a slow-moving lava flow front by a vigorous river, followed by transport and deposition of the glassy fragmental debris downstream (cf. Tolan and Beeson, 1984; Reidel et al., 2013). Pillow lavas also outcrop in the Dzoraget River canyon near Stepanavan (Fig. 1; Kh. Meliksetian, G. Navasardyan, M. Allen and I. Neill, 2011–2012 field data). These basalts also flowed along river valleys for tens of kilometres, and extend into southern Georgia (Kharazyan, 1983). One of these was dated at 2.5 ± 0.2 Ma by the K–Ar method (Chernyshev et al., 2002).

We envisage that the earliest Debed River basalt lavas entered river valleys and developed pillows in their deeper submerged parts, while their upper parts cooled subaerially, giving rise to sections such as the

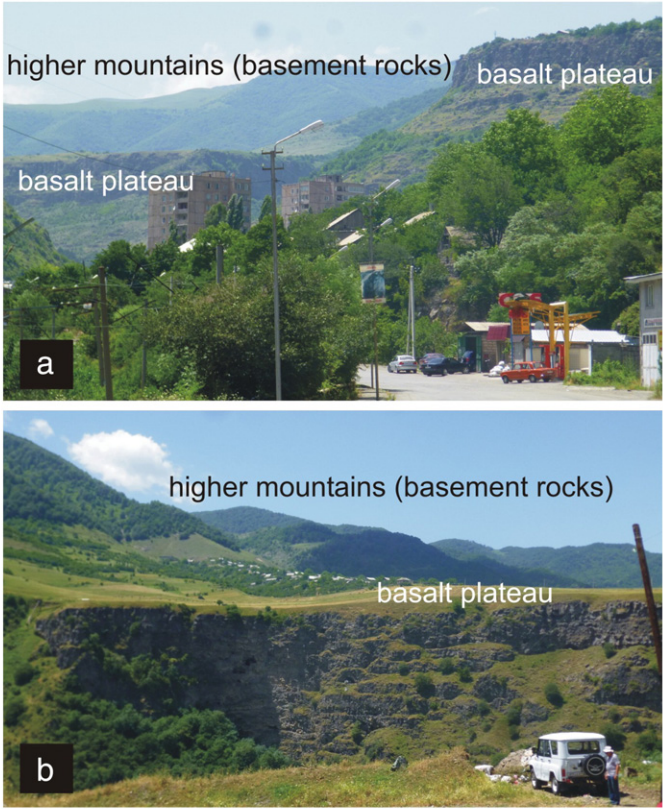

Fig. 3. Typical scenery of the Debed River basalts as seen from the level of the river along the Yerevan–Alaverdi road (a) and from the level of the basalt plateau (b). Note the typical stepped "Trap" landscape, and how the basalts have partly filled valleys between highlands made up of the basement rocks. This is how the Columbia River flood basalt province would have looked after the thick, intracanyon, Imnaha basalt lavas had erupted (e.g., Hooper, 1997; Reidel et al., 2013; S. P. Reidel, official review).

one shown in Fig. 5b (compare Fig. 8b of Tolan and Beeson, 1984). Damming of drainage by early flows may also have produced lakes into which later lavas flowed. The sharp and steep lateral contact between the pillow basalts and a columnar-jointed sheet flow at Tumanyan railway station (Fig. 5a) may represent a palaeovalley wall. Thick pahoehoe lava flows with pillowed bases, or the so-called "pillow-palagonite complexes", formed due to the entry of lavas into river valleys, are widespread in the Columbia River CFB province, as well as in Scotland, Ireland and Iceland (e.g., Saemundsson, 1970; Swanson and Wright, 1981; Long and Wood, 1986; Hooper, 1997; Lyle, 2000; Reidel et al., 2013).

3.3. Pahoehoe sheet flows with columnar tiers: terminology and theory

These flows have a tabular shape and columnar jointing (Spry, 1962), and before we describe them we briefly review the terminology and theory of formation for them. Such flows are often made up of two or more "tiers", each tier having a distinct jointing pattern. If there are two tiers, usually the lower one displays well-developed, parallel columns and is called "colonnade" (Tomkeieff, 1940). The upper tier may be another colonnade, but is commonly made up of very randomly oriented and thinner (≤10 cm) columns and is usually much thicker than the underlying colonnade. It is called "entablature" (Tomkeieff, 1940; Swanson and Wright, 1981; Fig. 6). The colonnade grows from the bottom of the flow upwards as the lava slowly cools by conduction, whereas the entablature grows from the surface of the flow downwards at a much more rapid rate which cannot be produced by conductive cooling. The rapid downward growth of the entablature (several times faster than the upward growth of the colonnade) is due to the ingress of large amounts of surface water (derived from very heavy rainfall or more probably flooding of the top of the lava flow by a blocked river) into the solidifying flow. The water enters the lava flow along master joints. Heat is rapidly removed by the resulting water-steam convection in the entablature, an inference supported by observations of cooling Hawaiian lava lakes, rapid-cooling textures and substantial glass in the entablature zones, and thermal modelling of heat loss from lava flows (Hardee, 1980; Long and Wood, 1986; Budkewitsch and Robin, 1994; Grossenbacher and McDuffie, 1995; Lyle, 2000).

Joint columns grow perpendicular to the isotherms (contours of equal temperature in a cooling lava), which are horizontal in the colonnade tier of a flat-lying tabular lava flow. Each columnar joint face grows by incremental crack propagation towards the molten interior of the lava flow, and these incremental fracturing events are identifiable by transverse bands on column faces, called "chiesel marks" (James, 1920) or "striations" (Ryan and Sammis, 1978; DeGraff and Aydin, 1987; DeGraff et al., 1989; Goehring and Morris, 2008) (Fig. 7a). In the entablature, surface water entering the lava flow strongly distorts the

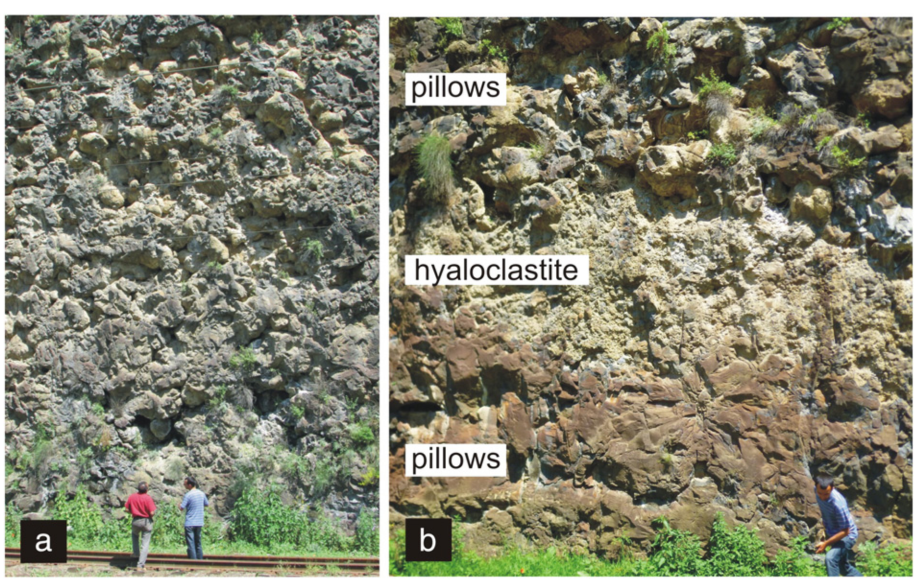

Fig. 4. (a) Cliff section of pillow basalts exposed beside the railway track a little south of Tumanyan railway station. (b) A close-up of the hyaloclastite horizon near the base and pillows above and below it. Note lower large pillow with radial cracks. Persons for scale.

Fig. 5. (a) Section beside the railway track exactly at Tumanyan railway station, showing a sharp and steep contact between a dipping, columnar-jointed sheet flow on the right and pillow basalts on the left. (b) Section a few kilometres north of Tumanyan, on the Yerevan–Alaverdi road, showing a pahoehoe sheet flow several tens of metres thick with its lower half pillowed. The upper, subaerially formed part of the flow shows an entablature above and a colonnade below. The cliff is ~50 m high. (c) Close-up of the pillow lavas in (b).

isotherms, and therefore columns develop in random orientations, everywhere perpendicular to the local shape of the isotherms. Curving and fanning shapes of entablature columns are thus common (Fig. 7b).

Many lava flows are known in which the entablature tier occurs in between an "upper colonnade" and a "lower colonnade", and still others display multiple alternating entablature and colonnade tiers. These features are ascribed to seasonal flooding of the lava top (producing rapid solidification and thus an entablature tier) separated by dry spells (producing slower solidification and a colonnade tier), as the whole flow progressively solidifies from the top down and from the bottom up over several years (Long and Wood, 1986). The contact between the entablature and the colonnade in a two-tiered flow, or between the lowest entablature tier and the lowest colonnade in a multi-tiered flow, is the last part of the lava flow to solidify (Long and Wood, 1986).

3.4. Pahoehoe sheet flows with columnar tiers: field observations

Pahoehoe sheet flows with columnar tiers form the thickest lava flows in the Debed River sequence, typically a few tens of metres thick and some >50 m thick. Some of the thick sheet flows exposed at the lower elevations have thick colonnades that are far from vertical and that cannot be explained by growing columns curving towards a nearby valley wall. This shows that the flows themselves have steep dips. An example is the lava flow shown in Fig. 5a, at Tumanyan railway station. Another very thick (several tens of metres) lava flow exposed at the lower elevations has a well-developed colonnade with gently dipping columns, suggesting that the flow itself is tilted to a near-vertical orientation, while the higher-level lava flows of the sequence are flat-lying (Fig. 7c, d). We provide an explanation below for the tilting of the earlier lava flows, and note that such tilted lava flows may also have provided barriers or dams across existing streams or rivers, forming lakes into which later lava flows (such as the pillow basalts around Tumanyan, Fig. 5a) flowed. Future detailed mapping of the structural relationships between these lower eruptive units will throw light on the concurrent tectonic deformation.

A good example of a multi-tiered pahoehoe sheet flow outcrops on the Vanadzor–Alaverdi road (Highway AM-61) a few kilometres south of Tumanyan (Fig. 8a). This flow has a pillowed base indicating a lower part submerged under water, and its subaerially formed upper part is made up of several tiers of entablature and colonnade. The entablature tiers are typically laterally discontinuous, and it is difficult to say whether this is a single multi-tiered flow (probable) or perhaps two or more flows. The colonnade tiers show well-developed, thicker and

Fig. 6. A two-tiered columnar-jointed basaltic lava flow with spectacularly developed entablature and colonnade, the former much thicker than the latter. Person (encircled) provides a scale. Kizilçahamam volcanics northwest of Ankara, Turkey. 2010 photo by H. Sheth.

vertical columns (Fig. 8a–c), whereas the entablature tiers show thinner column sets showing fanning and curved patterns (Fig. 8b), and even nearly horizontal columns (Fig. 8c).

Higher up in the sequence, on the road climbing up the escarpment to the town of Odzun (Fig. 1), is exposed a thick pahoehoe sheet flow displaying a lower colonnade with ~1 m wide columns and an upper

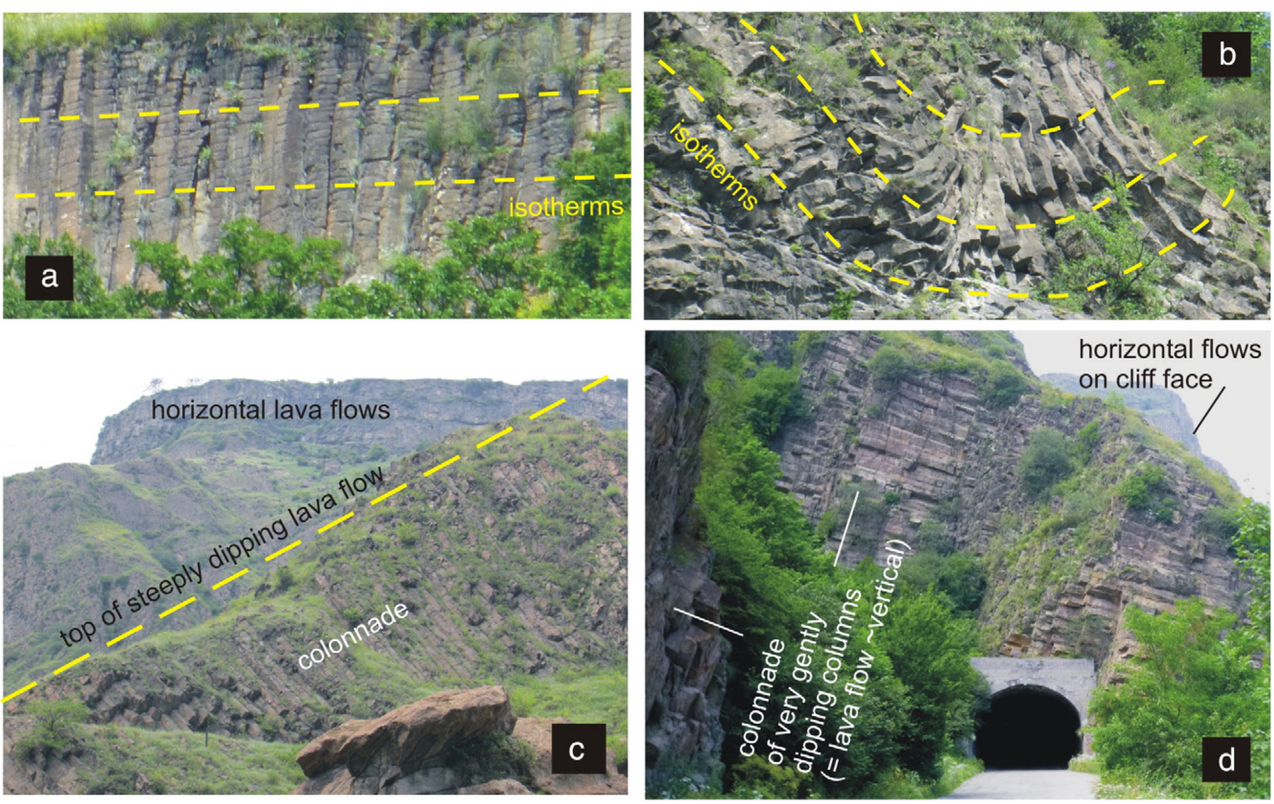

Fig. 7. Features of some Debed River columnar-jointed flows and evidence for tilting. (a) A very well-developed colonnade, ~5 m high, on the east side of the Yerevan–Alaverdi road south of Tumanyan. Note the very good development of horizontal chiesel marks on the columns. The interpreted isotherms are horizontal and shown by dashed lines. (b) An entablature zone with fanning columns in the upper part of the section shown in Fig. 5a. The interpreted isotherms, shown by dashed lines, are curved. (c) Very gently dipping, very thick colonnade of another sheet flow a little north of Tumanyan, showing that the flow itself dips very steeply away from the viewer. Note horizontal lavas capping the cliffs. (d) The lava flow in (c), with a colonnade dipping gently east (right), such that the colonnade can be seen in cross-section in the road cut (left margin of the photograph), whereas the flow itself dips very steeply towards the west, arguably due to tectonic tilting. The cliff face in the distance shows a vertical colonnade implying a horizontal lava flow. The tunnel through the strongly tilted flow provides an approximate idea of the scale.

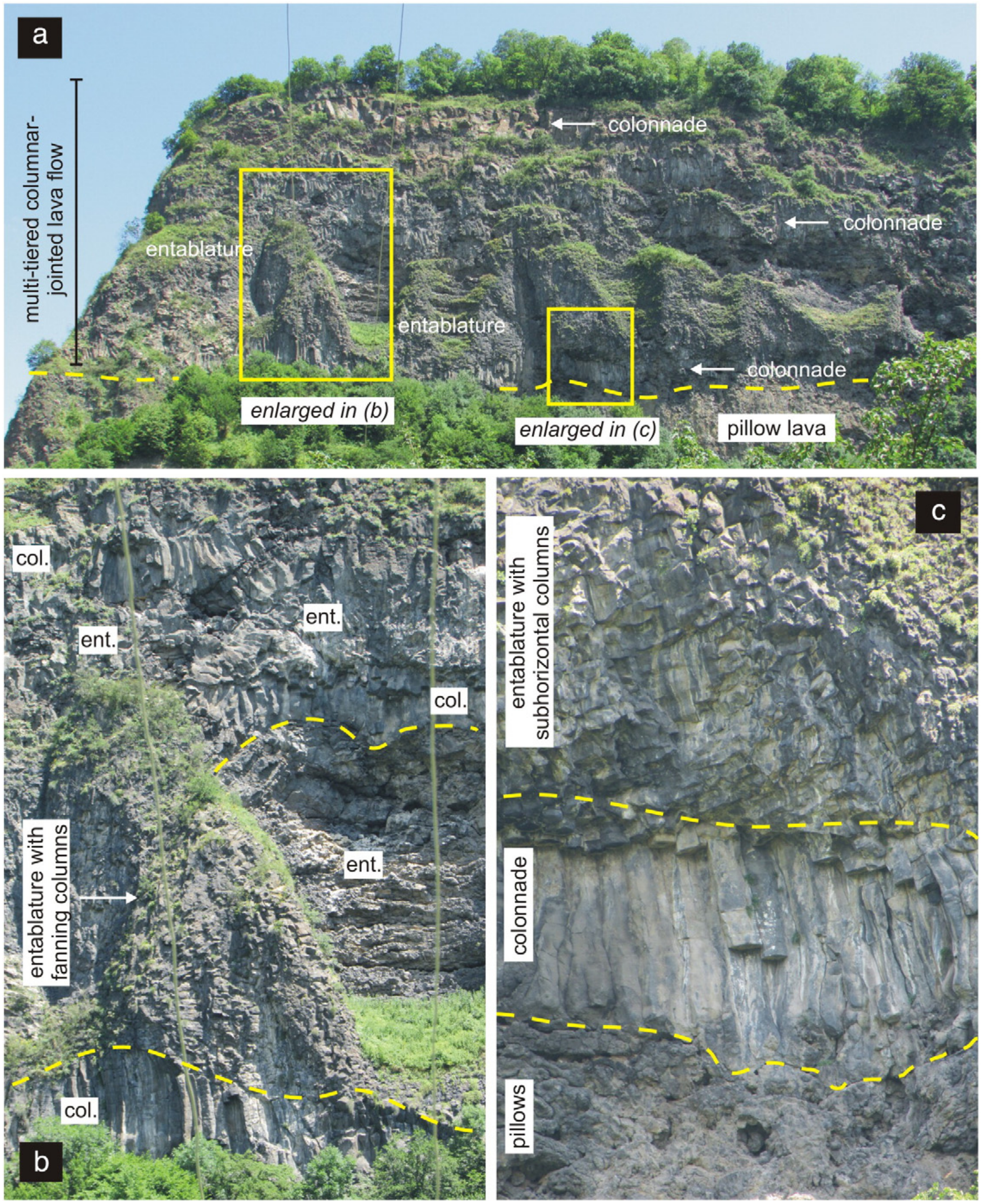

Fig. 8. (a) A well-developed multi-tiered columnar-jointed sheet flow several kilometres south of Tumanyan, on the east side of the Yerevan–Alaverdi road. The flow shows several colonnade and entablature tiers, the latter typically irregular, and some of them are separated by dashed lines. (b, c) Close-ups of parts of the multi-tiered flow, showing the column arrangements in the colonnade ("col.") and entablature ("ent.") zones, and the underlying pillows.

colonnade with even thicker columns. These two are separated by an entablature which is laterally discontinuous and shows hackly jointing (Fig. 9).

An ~230 m high cliff section in a table mountain ~3 km ENE of Alaverdi town exposes a sequence of at least five columnar-tiered sheet flows (exposed), capped by a stack of thinner slabby pahoehoe and rubbly pahoehoe flows (Fig. 10a, b). The sheet flows and their constituent tiers vary in thickness laterally. The flow shown in the upper third of Fig. 10b lacks an upper entablature and is made up of an upper and a lower colonnade, and corresponds to the Type I flows of Long and Wood (1986). The bases of both colonnades are broadly wavy (Fig. 10a, b). An underlying flow (in the middle part of Fig. 10b) has a thick entablature underlain by a variably thick colonnade.

3.5. Interpretation

Following Long and Wood (1986), we interpret the multi-tiered sheet flow in Fig. 8a as formed during several cycles of alternating very wet periods (corresponding to the entablature tiers) and dry periods (corresponding to the colonnade tiers). The whole flow therefore should have taken several years to solidify. The fanning column sets in the entablature in Fig. 8b indicate tilted and strongly curved isotherms, whereas the subhorizontal columns in the entablature in Fig. 8c indicate

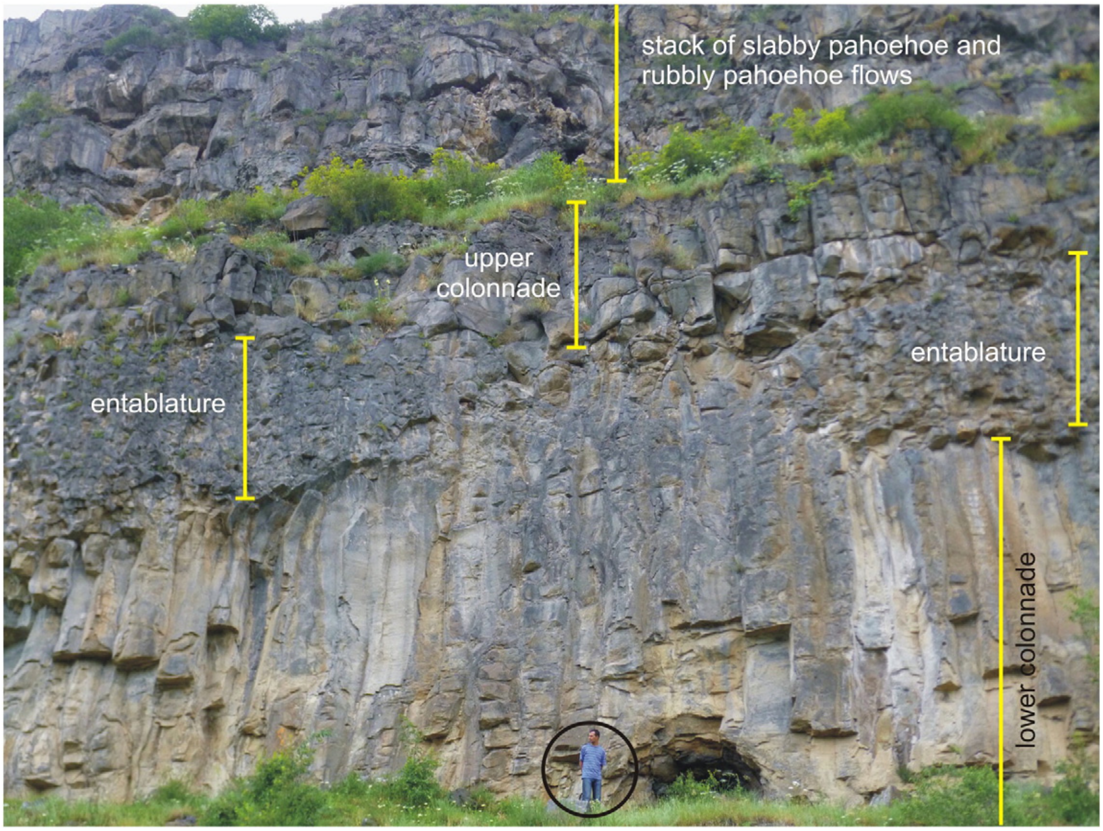

Fig. 9. Thick pahoehoe sheet flow with three tiers, on the road to Odzun. The flow has an upper colonnade, a laterally discontinuous entablature with hackly jointing below, and a well-developed lower colonnade with columns ~1 m wide below the entablature. Where the entablature is missing, as in the centre of the photo, the upper and lower colonnades are in mutual contact. The person (encircled) provides a scale.

that the isotherms were nearly vertical. The latter condition can be produced by sustained flow of water along vertical master joints or large fractures, which thus become secondary cooling surfaces (Long and Wood, 1986).

The flow in Fig. 9, with upper and lower colonnades separated by an entablature, would have experienced dry conditions on eruption, and cooled slowly, resulting in wide columns in the upper colonnade. A later wet season generated the entablature below the upper colonnade, and its laterally discontinuous nature implies that different amounts of surface water (probably flowing in distinct channels on the cooling flow) entered the lava at different locations.

The sheet flow with two colonnade tiers but lacking an entablature altogether (Fig. 10a, b; Type I flows of Long and Wood, 1986) was formed by two solidification fronts, one from above and the other from below, moving towards the interior of the flow at roughly equal pace. The cooling of both colonnade tiers was conductive and there was no involvement of surface water in the lava flow cooling, suggesting that this lava flow formed during a long dry period of several years. The thick flow below that flow, with an entablature and colonnade (Fig. 10a, b), corresponds to the Type III flows of Long and Wood (1986). We interpret this multi-tiered flow to have formed by simultaneous upward growth of the colonnade due to conductive cooling and much faster downward growth of the entablature due to water-steam convective cooling, indicating that surface water played a role in solidifying the flow from right after its emplacement. The part of the flow to solidify last was the boundary between the upper and the lower colonnades (cf. Long and Wood, 1986).

The sheet flows have laterally changing thickness because each of these fluid basaltic lavas moulded itself on the surface of the immediately older flow. The flows are therefore thicker over depressed areas in the top surfaces of the flows underlying them.

3.6. Slabby pahoehoe and rubbly pahoehoe flows

Flows with features transitional between pahoehoe and ‘a’ā, including slabby pahoehoe (Duraiswami et al., 2003) and rubbly pahoehoe (Keszthelyi and Thordarson, 2000; Duraiswami et al., 2008), constitute the upper part of the Debed River basalt sequence. They are well exposed on the road to Odzun village situated on the plateau top (Fig. 11a, b). A sequence of several transitional flows with pahoehoe slabs forming their uppermost crusts, with or without overlying flow-top breccia, is exposed here. Their upper and lower boundaries are generally horizontal, but one flow (above the centre of Fig. 11b) has a wavy cross-sectional outline reflecting the shape of the upper surface of the underlying flow.

Three of these transitional flows are visible in Fig. 12a. Each has a thick, dense, non-vesicular core with a thick upper crust, while the lower crust is poorly developed or absent. Three notable features of the upper crust (Fig. 12a, b, c) are: (1) it is increasingly vesicular upwards, (2) the vesicles form distinct parallel, horizontal trains, and (3) the vesicles are horizontally highly elongated, very distinct from the nearly spherical vesicles typical of pahoehoe (e.g., Macdonald, 1953). Given the increasing vesicle concentration upwards, the horizontal trains of elongated vesicles grade into definite horizontal partings inthe uppermost crust, producing well-developed lava slabs 10–30 centimetres thick (Fig. 12a–d). Some of these slabs have undergone brecciation to produce flow-top breccia which caps the preserved slabs (Fig. 12c). The individual slabs show brecciation on their upper surfaces, whereas their undersides display shark's tooth-like projections (Fig. 12d, e). The slabs are sometimes tilted and rotated, the flow-top breccia varies in thickness from a few to several tens of centimetres and can be locally absent in the same flow, and the boundaries of the flows may be locally uneven (Fig. 13).

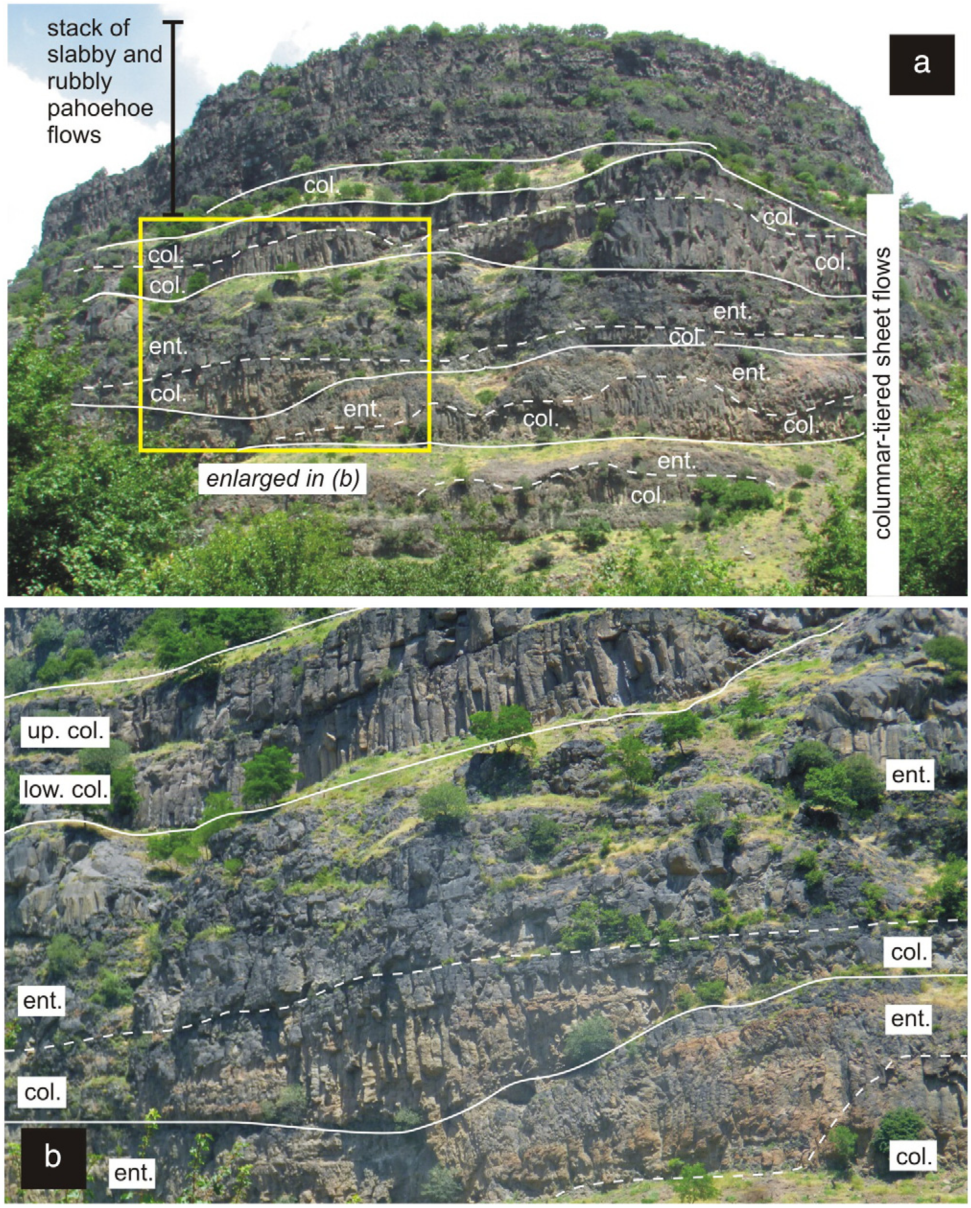

Fig. 10. (a) 230 m high cliff ~3 km ENE of Alaverdi, showing a sequence of columnar-tiered pahoehoe sheet flows capped by a stack of slabby pahoehoe and rubbly pahoehoe flows. The upper and lower boundaries of the sheet flows are indicated by continuous white lines, and the boundaries between the entablature ("ent.") and colonnade ("col.") tiers of individual sheet flows are indicated by dashed white lines. (b) Detail of a part of the cliff face (field of view is ~50 m high) showing the entablature and colonnade zones of three of the sheet flows.

Unlike the preserved upper crusts of pahoehoe, the flows shown in Figs. 11 to 13 have extensively fractured and brecciated upper crusts. They are also not 'a'ā flows because 'a'ā flows contain both flow-top and flow-bottom breccia or clinker, and being channelized, erode their bases (e.g., Macdonald, 1953; Lockwood and Hazlett, 2010, pp. 161–167). Slabby pahoehoe is an appropriate term for the transitional lava flows illustrated in Figs. 11–13 with their upper crusts broken into slabs (see e.g., Duraiswami et al., 2003), whereas transitional lavas with flow-top breccia and well preserved bases are properly described as rubbly pahoehoe (e.g., Duraiswami et al., 2008). The lava flow shown in Figs. 12a and 13 combines both types.

The flows exposed in this section show these same features repeating throughout the sequence (Figs. 11b, 12a, 13). Features otherwise typical of pahoehoe flows, such as vesicle cylinders and horizontal vesicle sheets (Self et al., 1997), are observed in some of the lava flow cores (Fig. 14a–c). The vesicles forming these features are more or less spherical.

3.7. Interpretation

As described by many authors (e.g., Kilburn, 1981; Rowland and Walker, 1990; Duraiswami et al., 2014; Murcia et al., 2014), lava morphologies reflect the cumulative effects of intrinsic parameters (composition, temperature, crystallinity, volatile content) and extrinsic parameters (eruption mechanism, effusion rate, topography and flow velocity). The upper flow shown in Fig. 13 filled the uneven topography of the lower flow containing the variably thick and loose flow-top breccia. The upper flow has a well-preserved base, indicating that it did not thermally or mechanically erode its substrate, and that these flows were emplaced in a gentle, effusive manner as pahoehoe flows do (e.g., Self et al., 1997). However, the parallel, horizontal trains of elongated vesicles in these lavas do not represent rising bubbles that were periodically captured at a progressively descending solidification front between the solid upper crust and the molten flow core, as in classical pahoehoe. Instead, the horizontally strongly elongated shapes of all vesicles indicate

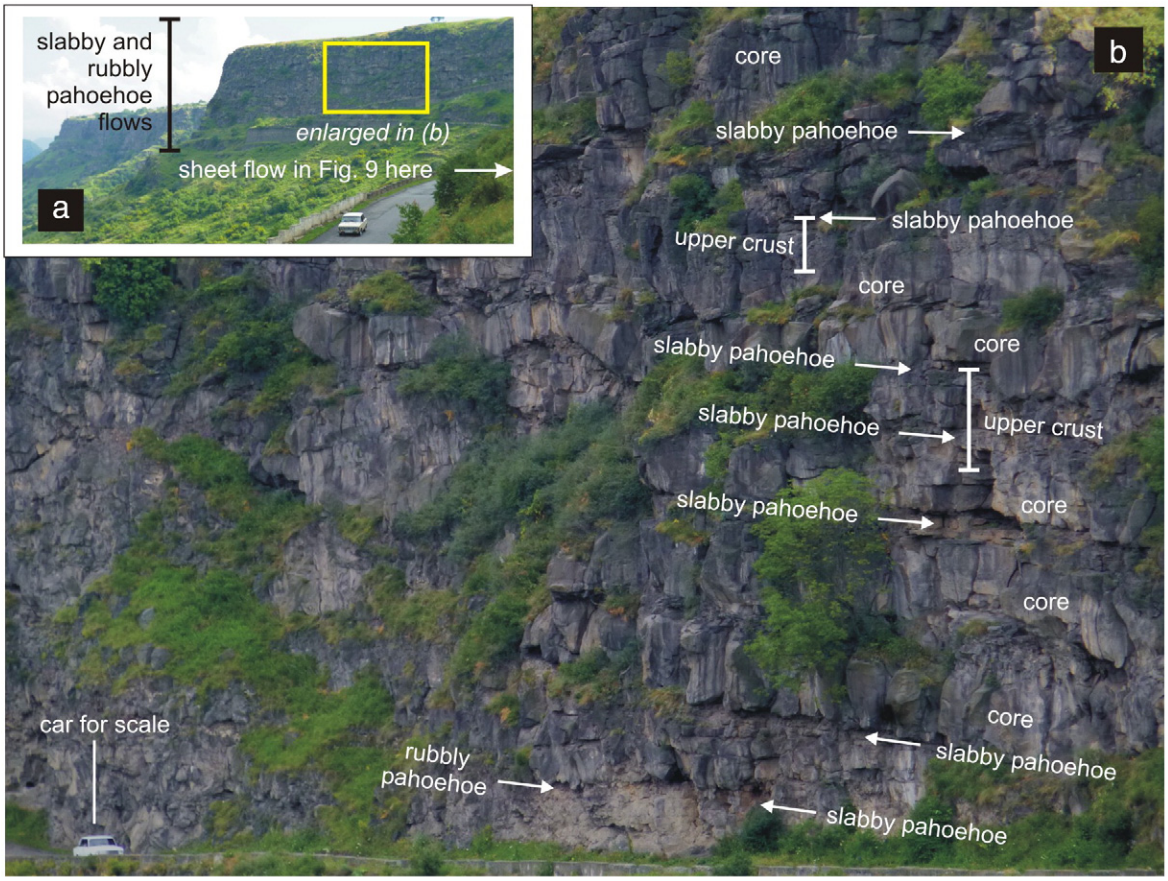

Fig. 11. (a) The typical plateau scenery of the Debed River flood basalts as seen from the road winding its way up to Odzun. (b) Close-up view of a part of the cliff face in (a), showing the detail of the stacking of the slabby pahoehoe and rubbly pahoehoe flows. Car provides a scale. The locations of several distinct levels of slabby pahoehoe, rubbly pahoehoe (marked by flow-top breccia), and some of the well-developed flow cores, are indicated.

that the bubbles in the upper crust were subjected to unidirectional shear (see Duraiswami et al., 2014). Such shearing of the visco-elastic crust can occur if the flux of the lava continuing to flow under the crust rises significantly leading to rapid flow inflation, or during large surges in the lava supply, as when lava temporarily ponded in a part of the lava flow is suddenly released in the downflow direction (e.g., Peterson and Tilling, 1980; Hon et al., 1994). Such surges lead to shearing and stretching of the vesicles (Polacci et al., 1999), followed by extensional fracturing of the crust (Kilburn, 2004). Pahoehoe slabs form from the increasingly degassed and viscous lava and can undergo rotations, collisions, and further fracturing, and flow-top breccia forms from the slabs as observed in Figs. 12c, 13. This suggests that whereas these flows did experience inflation as classical pahoehoe flows do (Self et al., 1997), their extensively fractured upper crusts (unlike the preserved crusts of pahoehoe) formed due to sudden and significant increase in lava supply before it waned again.

Slabby pahoehoe flows, and abundant rubbly pahoehoe flows, have been described from the Deccan CFB province, where (as in Figs. 12c, 13) pahoehoe slabs have often brecciated to form flow-top breccia and complete transitions from one to the other type exist (Duraiswami et al., 2014). Rubbly pahoehoe flows are also reported from provinces like the Columbia River flood basalts (e.g., Swanson and Wright, 1981; Bondre and Hart, 2008; Reidel et al., 2013) and from <4500 year old flood basalt fields in Saudi Arabia, in which they occur downflow from slabby pahoehoe (Murcia et al., 2014).

As regards the shark's tooth-like projections on the undersides of the pahoehoe slabs (Fig. 12d, e), we believe that these formed due to heating and melting of the undersides of the uplifted slabs by accumulating gas bubbles, producing lava drips, essentially lava stalactites. A similar interpretation has been made of centimetre-size lava stalactites observed at the base of slabs of shelly pahoehoe in <4500 year old Saudi Arabian lava flow fields (Murcia et al., 2014). The vesicle cylinders and horizontal vesicle sheets observed in the cores of the Debed River transitional flows (Fig. 13a–c) formed after lava supply to the flow finally stopped and the lava in the core became stagnant, preserving these features and the near-spherical shapes of the individual vesicles.

4. Discussion

4.1. The absence of sedimentary interbeds or palaeosols

We have mentioned that the Debed River basalts are intracanyon flows filling river valleys, and in such an environment there is an opportunity for inter-flow sedimentation. Though Kharazyan (1966) mentioned local sedimentary interbeds in the Debed River, we have not observed them in the sections we examined, and they also do not occur among the basalts in the Dzoraget and Akhuryan River canyons (Kh. Meliksetian, G. Navasardyan, M. Allen and I. Neill, 2011–2012 field data). Thus the virtual absence of sedimentary interbeds (or palaeosols) in the Debed River basalts suggests that the successive eruptions followed each other rapidly, without significant time gaps.

Inter-flow sedimentary beds are similarly absent in the major eruptive phase of the Columbia River flood basalts, and only developed during the waning phases of the volcanism when successive eruptions were separated by substantial time intervals (e.g., Reidel, 1998; Reidel et al., 2013).

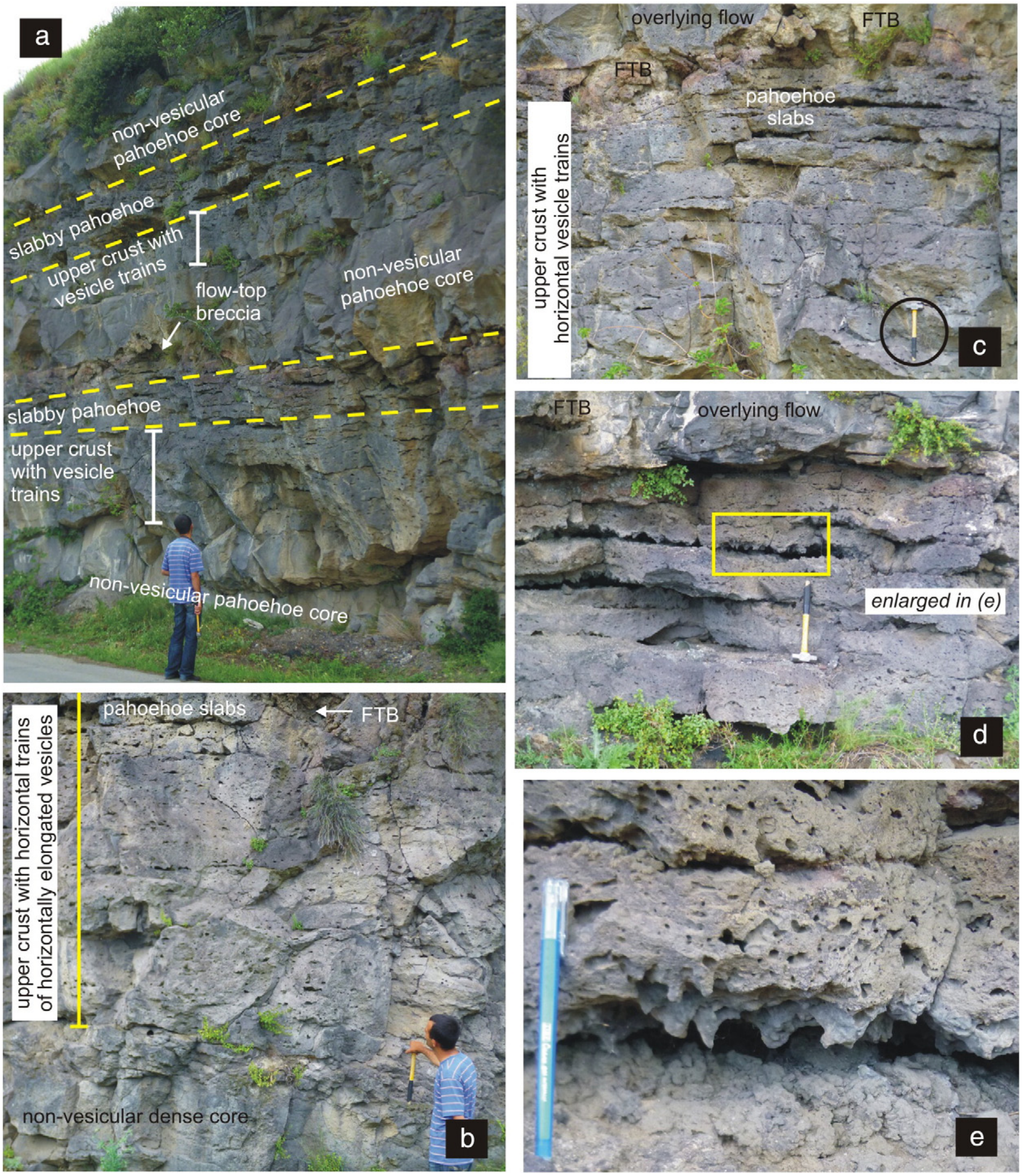

Fig. 12. Details of the slabby pahoehoe and rubbly pahoehoe flows forming the upper part of the Debed River sequence, as seen in the cliff face in Fig. 11a. (a) Three successive slabby pahoehoe flows, with dense, non-vesicular cores, overlain by a thick upper crust with horizontal trains of elongated vesicles, grading upwards into distinct pahoehoe slabs, which in the lowermost flow grade into flow-top breccia. (b, c) Close-ups of the slabby pahoehoe flow with a dense core, overlain by upper crust containing horizontal trains of horizontally elongated vesicles, grading into pahoehoe slabs and then into flow-top breccia (FTB). Person in (b) and hammer (encircled) in (c) provide a scale. (d) Slabby pahoehoe in vertical section, showing a succession of six slabs (10–30 cm thick), with gaps between some slabs and rough undersides of the slabs, as well as local FTB. Hammer for scale. (e) Detail of parts of three of the pahoehoe slabs shown in (d), showing the stretched vesicles in the slabs, complete opening of the lower and middle slabs' contact, brecciation of the upper surface of the lower slab, and shark's tooth-like lava stalactites on the underside of the middle slab. Pen is 15 cm long.

4.2. Interplay of tectonics and volcanism

We described above the field evidence for tectonic tilting of some of the lower Debed River lavas, with the middle and upper lavas being horizontal (Figs. 5a, 7c, d). Thus, faulting was ongoing during the early eruptions and its cause needs to be explained. The interior of the Turkish–Armenian–Iranian plateau is crossed by many active strike-slip fault systems. These systems, which often exploit pre-existing crustal discontinuities, have produced highly localized pull-apart zones along which Quaternary magmatic activity has been located (e.g., Karakhanian et al., 2002; Karakhanian and Abgaryan, 2004; Meliksetian, 2013). In Armenia, the active, right-lateral strike-slip Pambak–Sevan–Syunik fault system (Fig. 1) runs along the Sevan–Akera suture. Neill et al. (2013) noted that the basalts of the Lori Plateau

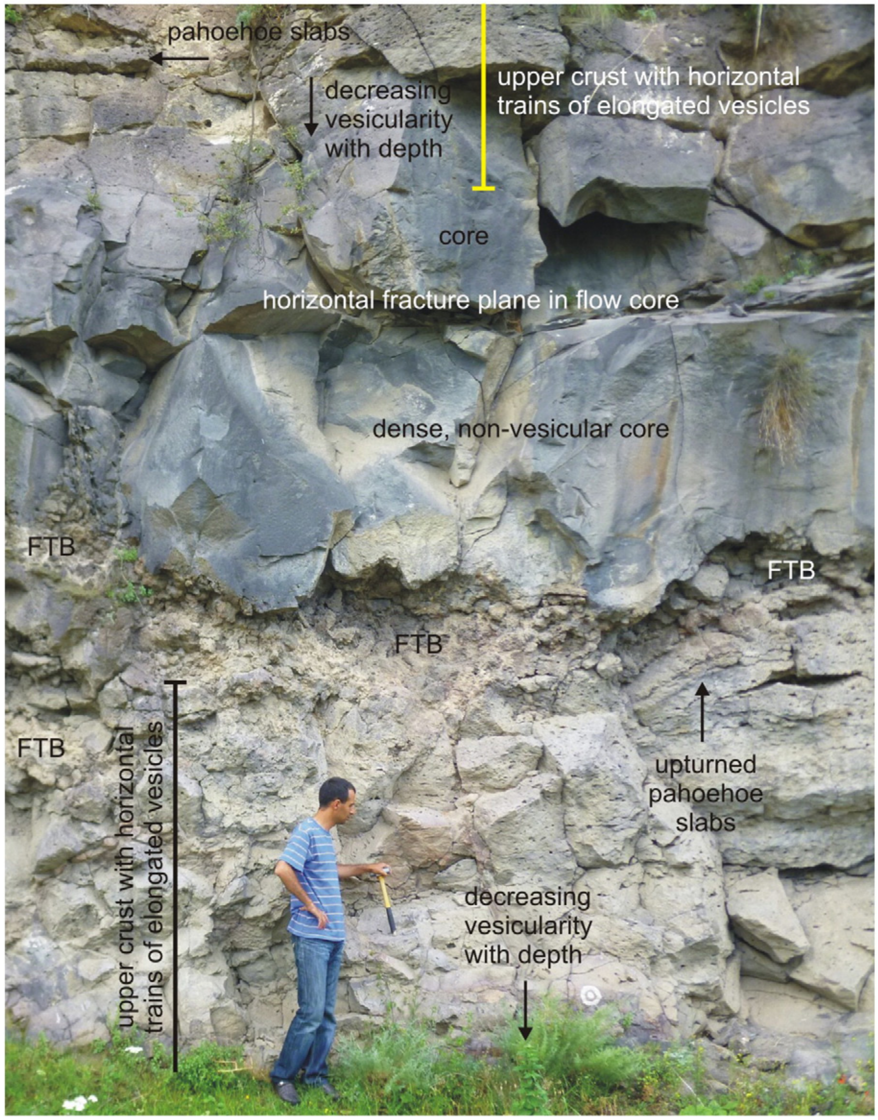

Fig. 13. Road cut exposure showing a lower flow combining the slabby pahoehoe and rubbly pahoehoe characters, overlain by another flow grading into slabby pahoehoe at its top. Note the tilted pahoehoe slabs of the lower flow to the right, grading into flow-top breccia (FTB), and the absence of slabs and the much thicker flow-top breccia in the lower flow near the centre of the photo, implying that the slabs here completely brecciated to produce the FTB. Note also how the upper flow has accommodated itself to the irregularities of the upper surface of the lower flow, without eroding or incorporating the loose FTB.

outcrop just north of this fault zone, and proposed that there was localized crustal extension at the time of the basalt volcanism as the region was experiencing pull-apart due to right-lateral strike-slip faulting along the Sevan–Akera suture. The faulting that accompanied the early eruptions of the Debed River basalts can therefore be viewed in this broader context of transtensional crustal movements. Interestingly, similar strike-slip faulting ongoing during early flood basalt volcanism is reported from the Columbia River flood basalt province (e.g., Anderson et al., 2013).

4.3. The South Caucasus basalt province as a continental flood basalt (CFB) province

Lyle (2000) has illustrated flood basalt lavas with well developed colonnades and entablatures from provinces such as the Palaeogene North Atlantic Province in Scotland and Ireland, from Iceland, and the Columbia River Plateau flood basalt province. The spectacular multi-tiered flows of the Columbia River flood basalts have also been described by many workers, including Waters (1960), Swanson and Wright (1981), Long and Wood (1986), DeGraff and Aydin (1987), Hooper (1997), Self et al. (1997), Goehring and Morris (2008), and Reidel et al. (2013). The columnar pahoehoe sheet flows with pillowed bases observed in the Debed River canyon (e.g., Fig. 5b) are remarkably similar to those examples. The similarities are in fact so striking that the Debed River basalts (and their counterparts elsewhere in Armenia, Georgia and Turkey) can be considered a small analogue of the intracanyon flows of the Columbia River (e.g., Tolan and Beeson, 1984; Reidel et al., 2013) and other CFB provinces.

The total area of 3.25–2.05 Ma basalts in southern Georgia and northern and central Armenia is ~3300 km^2, and its approximate volume is ≥400 km^3. Fig. 15 shows the basalts in the canyon of the Akhuryan River at the Armenia–Turkey border, and forming the Kars–Erzurum Plateau in the distance, where their area is unknown because they are partly overlain by Quaternary lavas. We estimate these basalts' areal extent in the Kars–Erzurum Plateau at ~12,000 km^2 based on an old geological map (Erentoz, 1961). This yields a total areal extent of basalts across NE Turkey, northern and central Armenia, and southern Georgia of ~15,000 km^2. Assuming an average thickness of 150 m, the volume is ≥2250 km^3. We name this single ~3.25–2.05 Ma basalt province the South Caucasus province (Fig. 2).

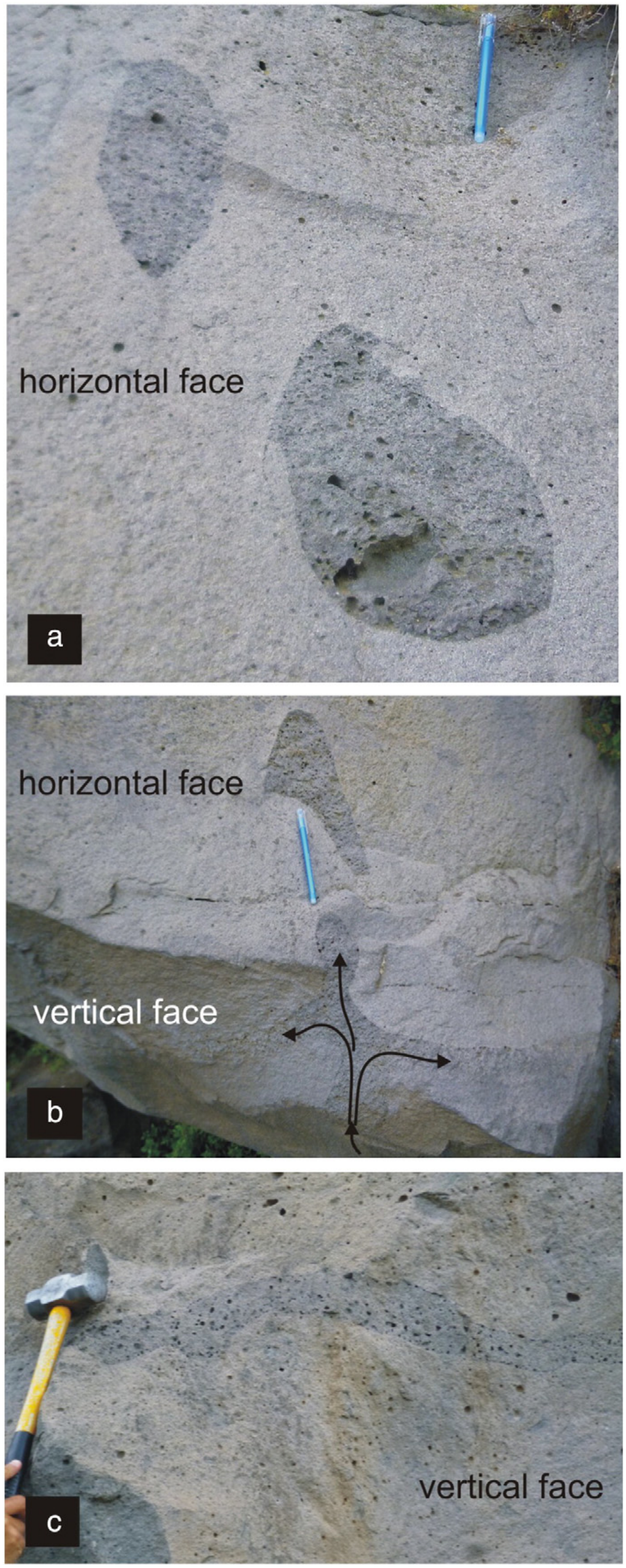

Fig. 14. Blocks of the slabby pahoehoe cores exposed in the cliff face in Fig. 11a, b, showing (a) two vesicle cylinders in cross-section, (b) a vesicle cylinder in cross-section (horizontal face) and another in profile giving rise to a horizontal vesicular sheet (vertical face). The interpreted movement directions of the very volatile-rich residual lava rising through the stagnant lava are shown by the thin black arrows. Pen is 15 cm long. (c) Another block of the core showing a vesicle sheet.

How closely does the South Caucasus province resemble continental flood basalt (CFB) volcanism? CFB provinces are usually envisaged as large in areal extent and volume, and the classical examples such as the vast Siberian or Deccan Traps, and even the smaller (210,000 km^2, Reidel et al., 2013) Columbia River province, are indeed orders of magnitude larger than the South Caucasus province. However, we consider the South Caucasus province a true, if small, CFB province, for the following reasons: (1) Over its entire extent it is composed of horizontally stacked basalt sheets (see Figs. 3, 10, and 15, and Fig. 7 of Lebedev et al., 2008a). (2) These basalts were erupted rapidly, as indicated by the absence of sedimentary interbeds or palaeosols. (3) The lavas were highly fluid and flowed along river valleys for many tens of kilometres. (4) Point sources such as scoria cones cannot have fed these lava flows. Instead, these lavas erupted from fissures, and the potential eruptive fissures of the Debed River basalts are seen in subvertical dykes exposed in the canyon walls above Alaverdi town (Fig. 1). (5) The South Caucasus basalts show remarkable similarities in morphological features, architecture, and eruption environments to other flood basalts of the world. (6) They also show close geochemical similarities to flood basalts such as the Deccan Traps (Meliksetian et al., 2014). (7) "Intermediate-size" tholeiitic and alkalic flood basalts have been described from Libya (Németh et al., 2003), Patagonia (Németh et al., 2007), and Saudi Arabia where individual basaltic fields ("harrats") cover 900–46,000 km^2 (Camp et al., 1991; Murcia et al., 2014). Taken together, the large, intermediate-size and small CFB examples imply that there are no natural breaks in size CFB size distribution, which is a continuum (see also Cañón-Tapia, 2010).

4.4. An analogue of the South Caucasus CFB province: Altos de Jalisco (Mexico)

We have given above several reasons for considering the South Caucasus basalt province as a small CFB province. We mention here another basalt province which is generally not recognized as a CFB province owing to its small size, but which shows all major CFB features and is a very close analogue of the South Caucasus province. This is the Late Miocene Altos de Jalisco basalt province in the western part of the Trans-Mexican Volcanic Belt (Mori et al., 2009). These plateau-forming, flat-lying basalts cover 8000 km^2 and are up to 700 m thick (see Fig. 3 of Mori et al., 2009). Their similarities to the South Caucasus basalts are striking: (1) The Altos de Jalisco basalts were mainlyextruded as fissure eruptions within less than 1 million years as shown by K–Ar ages. (2) They lack erosional contacts, palaeosols or sedimentary interbeds, indicating rapid eruptions. (3) They flooded a pre-existing depression cut into Early Miocene ash flows of the Sierra Madre Occidental, and (4) their emplacement was favoured and controlled by pre-existing zones of crustal weakness, which were reactivated in a transtensional fashion during the Late Miocene (Ferrari et al., 2000; Mori et al., 2009). These features suggest that the Altos de Jalisco and the South Caucasus basalt provinces are perfect analogues of each other, and both should be considered small CFB provinces noting their close similarities to the classical, larger CFB provinces already described.

The 17–5 Ma Columbia River CFB province, occupying 210,000 km^2, is usually considered the world's smallest and youngest CFB province (e.g., Reidel et al., 2013). The 3.25–2.05 Ma, ~15,000 km^2 South Caucasus province should now be considered the smallest and youngest CFB province.

4.5. Small CFB provinces: implications for geodynamic models

We expect that, besides the Altos de Jalisco CFB province in Mexico, there will be other analogues of the small South Caucasus CFB province. These raise some interesting and important broader questions. For example, these CFBs are too small for mantle plumes to be invoked, and the South Caucasus CFB province formed in a collisional setting

Fig. 15. View of the flood basalts exposed in the Akhuryan River canyon at the Turkey–Armenia border, and the Kars–Erzurum Plateau of Turkey (behind the canyon). Photo by Kh. Meliksetian.

(Keskin et al., 1998; Neill et al., 2013; Meliksetian et al., 2014). Should we then consider that the larger CFBs of the world formed from mantle plumes but the small CFBs did not? If no natural breaks exist in CFB size distribution, where do we draw the line between small (arguably "non-plume"), and big (supposedly "plume") provinces? And, if the smaller CFBs resembling the large ones in all major features (except size) do form by non-plume processes, why cannot the larger ones? A full discussion of these issues is beyond the scope of the present work. However, Sheth (2007) has examined the term "flood basalt", and states that the term is a "valid descriptor of large-volume lava flows of high fluidity that produce essentially flat landscapes by inundating and filling pre-existing topography". This is exactly what the basalt lavas of the South Caucasus province have done. The term CFB must be applied to provinces based on their physical features, independent of tectonic setting (Sheth, 2007; Cañón-Tapia, 2010).

4.6. Future work

The Debed River flood basalts are poorly known in the international literature and the same can be said about the South Caucasus CFB province. We have provided here a description of the morphology, architecture and eruption environments of the Debed River basalts which, as seen in Fig. 2, constitute a small part of the whole province. Our work should however serve as a useful guide and model to future volcanological studies of the entire province. Much work remains to be done, following the lines of research followed on flood basalts like the Deccan or the Columbia River. This includes: (1) detailed field-based volcanological work and logging of sections and characterization of lava morphotypes (see e.g., Duraiswami et al., 2014; Murcia et al., 2014), (2) stratigraphically controlled sampling, (3) $^{40}Ar/^{39}Ar$ dating and magnetic polarity studies of key, stratigraphically constrained lava flows, as well as intrusions, as tools for stratigraphic correlation, (4) geochemical analyses of the lavas and intrusions as additional tools for stratigraphic correlation and for petrogenetic interpretations, expanding the database of Neill et al. (2013) and Meliksetian et al. (2014), (5) tracing and mapping the Debed, Dzoraget and Akhuryan River flood basalts into neighbouring Georgia and Turkey, with similar follow-up work, and (6) province-wide stratigraphic correlations, eruptive models, and geodynamic modelling. Sustained and coordinated research efforts over the next decade can surely make the South Caucasus CFB province internationally famous for its spectacular exposures and the role it has to play in our conceptual understanding of CFB volcanism.

5. Conclusions

The Late Pliocene to Early Pleistocene (~3.25–2.05 Ma) South Caucasus basalt province, covering parts of Turkey, Georgia and Armenia, is a small continental flood basalt (CFB) province with an estimated areal extent of ~15,000 km^2 and volume of ~2250 km^3. It is the world's smallest and youngest CFB province. Its fissure-fed, rapidly erupted, highly fluid basalt lavas flowed along pre-existing river canyons for many tens of kilometres, and built plateaus of horizontally stacked basalt sheets without significant eruptive hiatuses. The same basalts are also found in the Gegham Uplands and the Hrazdan River canyon in central and western Armenia. We have discussed the volcanological features and eruption environments of the ~200 m thick flood basalts exposed in the Debed River canyon in northern Armenia. They show three morphological types: basal pillow basalts and hyaloclastites, columnar-tiered pahoehoe sheet flows, and slabby pahoehoe and rubbly pahoehoe flows at the top. The lower two types indicate lava flows damming river valleys and displacing drainage, as is known for many lavas of the Columbia River CFB province, Scotland, Ireland, and Iceland. An excellent analogue of the South Caucasus CFB province, in all major features, is the Altos de Jalisco flood basalt province in the western Trans-Mexican Volcanic Belt. Both these provinces, though small, have important implications for our conceptual understanding of CFB volcanism and for geodynamic models.

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