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# Location of the River Euphrates in the Late Miocene; dating of terrace gravel at Shireen, Syria

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## Abstract

We report gravel of the River Euphrates, capped by basalt that is Ar-Ar dated to ~9 Ma, at Shireen in northern Syria. This gravel, preserved by the erosion-resistant basalt, allows us for the first time to reconstruct the history of this major river during the Late Miocene. In response to progressive regional surface uplift, the Euphrates extended SE by ~800 km between the early Middle Miocene, when the coast was near Kahramanmaraş in southern Turkey, and the Pliocene, when it lay in western Iraq, east of the Arabian Platform uplands.

## 1 Introduction

Due to their action of transporting the products of erosion, and thus facilitating the isostatic rebound that has contributed to the systematic growth of topography in the Late Cenozoic, large rivers have had a significant role in long-timescale global change. However, relatively few pre-Pleistocene upland localities are known with demonstrable evidence that a major river was present. Examples include: Australian rivers with records back to the Palaeogene (Stevenson and Brown, 1989; Nott, 1992); rivers in eastern Europe that are documented back to the Late Miocene (e.g., Matoshko et al., 2004); and the Colorado in the SW USA that has been reconstructed back to the Middle Miocene (e.g., McKee and McKee, 1972; Lucchitta, 1979). However, in most other regions one can only infer roughly where rivers once flowed from the provenance of sediment reaching lowland or offshore depocentres, with no direct supporting evidence.

With a length of ~2800 km, the Euphrates is the longest river in SW Asia. From its source in NE Turkey it flows initially west and south, then SE across the Arabian Platform in Syria and Iraq (Fig. 1) to the Persian Gulf. The Arabian Platform was a marine depocentre until the Middle-Late Miocene (e.g., Lovelock, 1984). Fluvial sand and gravel are widespread near its northern margin around Kahramanmaraş (e.g., Derman, 1999; Fig. 1), dated to the early Middle Miocene (Langhian; ~16 Ma) using interbedded

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basalt (Arger et al., 2000) and shallow marine sediments (Karig and Kozlu, 1990). The diverse clast content, including metamorphic lithologies not found in situ in the Arabian Platform, indicates that a major river, draining at least part of the modern upper Euphrates catchment, reached the sea here at this time (1, Fig. 1).

5 A staircase of Late Cenozoic fluvial terraces records the evolution of the Euphrates along its present course, indicating net incision by  $\sim 110$  m at Birecik (Sanlaville, 2004; Demir et al., 2004), near the Turkey-Syria border, and by  $\sim 70$  m at Khan al-Baghdadi (Tyráček, 1987) at the eastern margin of the Arabian Platform uplands (Fig. 1). Across  
10 eastern Syria (around and below Raqqa, where much less incision has occurred since both the Late Pliocene and the late Early Pleistocene; Westaway et al., 2005a) and western Iraq, the modern Euphrates valley is flanked by extensive older stacked fluvial gravels (attributed to the ancestral Euphrates from their diverse clast content), which indicate the course of the river in the Early Pliocene (e.g., Besançon and Geyer, 2003; 3, Fig. 1). However, its modern course farther upstream (4, Fig. 1) is no older than  
15  $\sim 2$  Ma, from the ratio of the offset of its gorge through the East Anatolian fault zone (EAFZ) to the total slip on this fault zone (e.g., Westaway, 2004).

There is thus a significant information gap, spanning the Late Miocene and more, for which the geometry of the Euphrates has been obscure. One view (Arger et al., 2000) has been that it terminated in a large palaeo-lake north of the modern Atatürk Dam  
20 (Fig. 1). Another possibility, suggested by the modern drainage geometry (Fig. 1), is that it flowed SW into the Mediterranean Sea, along either the Karasu Valley or the line of the modern River Ceyhan (Fig. 1), before being diverted eastward, possibly due to the initiation at  $\sim 4$  Ma of the modern geometry of the northern Dead Sea Fault Zone (DSFZ), which is strongly transpressive, with left-lateral slip accompanying localised  
25 surface uplift (e.g., Westaway, 2004; Seyrek et al., 2006). The most recent estimate of the initiation of this modern geometry of strike-slip faulting is  $3.73 \pm 0.05$  Ma (Westaway et al., 2006a), based on evidence from the SW part of the EAFZ to the east of Kahramanmaraş (Fig. 1). Previous work on reconstructing Plio-Pleistocene fluvial systems in Syria (Bridgland et al., 2003) and Turkey (Westaway et al., 2004, 2005b,

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2006b) has required the documentation of fragmentary sedimentary sections, often with dimensions of only a few square metres. We have identified one such site, at Shireen in northern Syria (Fig. 1), where fluvial gravel – attributed to the Euphrates and preserved due to capping by basalt – has been dated to ~9 Ma by Ar-Ar dating of the basalt, thus demonstrating the location of this major river in the Late Miocene.

## 2 Regional geology and tectonics

Most outcrop in this part of northern Syria (Fig. 2) consists of Cenozoic marine carbonates. Late Eocene chalky and clayey limestone is overlain by ~70 m of Oligocene hard crystalline limestone and dolomitic limestone (Ponikarov et al., 1967). During deposition of these sediments the northern Arabian Platform formed a seaway linking the Mediterranean Sea and Indian Ocean.

Unconformable Miocene marine limestone was assigned by Ponikarov et al. (1967) to the Jeribe Formation. This stratigraphic unit has regional significance, extending from Syria to Iran, dated to the early Middle Miocene (Langhian; James and Wynd, 1965; Alsharhan and Nairn, 1995). Diverse carbonate facies are evident, suggesting rapidly-changing shallow-marine conditions. This limestone is overlain by deposits assigned by Ponikarov et al. (1967) to the Lower Fars Formation, another regionally significant unit, of late Middle Miocene (Burdigalian) age (James and Wynd, 1965; Alsharhan and Nairn, 1995). Around Shireen this consists of interbedded green calcareous clay and marl, red mudstone and white limestone with occasional gypsum layers, and is no more than a few tens of metres thick. Farther north near the Turkish border, conglomerate and cross-bedded sandstone are also assigned to this unit. These sediments indicate marginal marine conditions with input of clastic sediment from the north. By this time a land bridge connected Arabia with Turkey (between Aleppo and Kahramanmaraş; Fig. 1), isolating the Mediterranean Sea from the Mesopotamian Basin of Syria, Iraq and Iran.

No younger stacked sediments are found in this area. However, east of Raqqa

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(Fig. 1) there is extensive outcrop of the Upper Fars Formation, consisting of up to ~250 m of clay, siltstone, fine-grained sandstone and gypsum. These deposits record a marine to lagoonal or lacustrine transition, which occurred in the Late Miocene (James and Wynd, 1965; Alsharhan and Nairn, 1995). Younger stacked terrestrial sediments, assigned to the Pliocene and correlated with the Bakhtiari Formation of Iraq, also crop out widely in eastern Syria, notably around Deir ez-Zor. These consist of sand and gravel, with a general upward-coarsening trend, with calcareous clay and gypsum interbeds (Ponikarov et al., 1967), indicating a lacustrine depocentre with fluvial input. The clasts include igneous and metamorphic rocks derived from eastern Turkey, indicating that the Euphrates reached the area at that time (3, Fig. 1).

Following the Eocene closure of the Neotethys Ocean (see Fig. 1 caption), northward motion of the African Plate (AF) was accommodated for tens of millions of years by distributed crustal shortening. The principal shortening mechanism within the Arabian Platform involved folding of anticlines above blind reverse faults (e.g., Rigo de Righi and Cortesini, 1964; Chaimov et al., 1990; Coşkun and Coşkun, 2000). The DSFZ developed in the early Middle Miocene (~19 Ma; Garfunkel, 1981), separating the Arabian Plate (AR) from the African Plate. Initially, it seems, its left-lateral slip was taken up by continued distributed shortening within the northern Arabian Platform (Westaway, 2004). At ~4 Ma (Westaway, 2004; Westaway et al., 2006a; Seyrek et al., 2006) the modern throughgoing linkage (Fig. 1) between the DSFZ and EAFZ developed, since when many of these anticlines have been inactive. However, the northern DSFZ is strongly transpressive (e.g., Westaway, 2004; Gomez et al., 2006; Seyrek et al., 2006). The component of distributed shortening along it has caused localised growth of topography (e.g., Westaway, 2004), notably in the Lebanon Mountains, Syrian Coastal Range and Amanos Mountains (Fig. 1). Superimposed on all these local effects has been progressive southward regional tilting of the land surface, due to the typical northward increase in rates of post-Middle Miocene regional uplift (e.g., Arger et al., 2000). All these factors, plus the need to maintain a downstream channel gradient, must be considered when reconstructing the evolution of the Euphrates.

### 3 The Shireen site

The site is in the left flank of the Euphrates valley (~35 km S of the Turkish border, ~60 km downstream of Birecik), ~4 km E of the modern river, whose course locally bends from SE to SW (Figs. 1, 2). This region is transected by both SE- and SW-trending reverse faults, which took up crustal shortening prior to the initiation of the EAFZ, causing localised offsets and warpings in the stacked Cenozoic sediments. The present local relief results from this deformation, differential erosion (the Eocene clayey limestone being easily erodable) and fluvial incision. Young incision is revealed by Euphrates terraces (Table 1), the most prominent around Shireen being QfIII and Qf0 (Fig. 2), the latter assigned to MIS 2 (Fig. 3).

About 2 km SE of Shireen, the road along the Euphrates valley passes through basalt, which unconformably overlies the stacked Middle Miocene succession (Fig. 2). At UTM co-ordinates [DA 37748 47784], a track heads west to a quarry, where the basalt overlies gravel (Fig. 4). The up to ~1 m thickness of gravel visible (base not exposed) is cemented and highly weathered. Clasts, set in a sandy matrix, and typically rounded to subrounded, are poorly-sorted but show stratification and some evidence of fining-upward (maximum size, ~10 cm). Intact clasts of both chert and limestone are abundant, the largest being of limestone, but clasts of other lithologies have weathered to powder or disintegrated completely, leaving voids within the matrix. The cemented nature of the deposit and the fact that many clasts are unidentifiable have precluded any stone count analysis. The basalt-gravel contact is subhorizontal, except at the left-hand (south) end of the exposure, where the basalt covers a downward bluff at the edge of the gravel (Fig. 4b). The ~3 m of basalt is likewise highly weathered. Above the quarry face the in situ basalt is obscured by a pediment of basalt blocks, whereas within this face it consists of corestones surrounded by rotten rock. Sample 03SY09 was collected from a corestone for Ar-Ar dating.

This basalt erupted from a neck at ~440 m a.s.l., 1.6 km SSW of this site (Fig. 2). It flowed initially east for 1 km before apparently becoming deflected northward along a

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local tributary valley, descending from ~400 to ~370 m a.s.l. in 1 km distance. However, the most distal ~1 km of this flow, including this site, is at a roughly constant level of ~370 m a.s.l. The “Early Pleistocene” age of this basalt, shown on the local geological map sheet, seems to have been inferred (Ponikarov et al., 1967) by analogy with the Pleistocene basalts in the nearby Karasu Valley (cf. Yurtmen et al., 2002; Seyrek et al., 2006). However, the degree of weathering is more characteristic of the Late Miocene Homs basalt of western Syria (~6 Ma; Mouty et al., 1992) and Karaçay basalt of SW Turkey (~7 Ma; Westaway et al., 2005b). Ar-Ar dating indeed gave an age of  $8809 \pm 73$  ka ( $\pm 2\sigma$ ) for our sample (Fig. 5).

## 4 Discussion

Although exposure and preservation are not ideal, we interpret the gravel in Figs. 3 and 4 as fluvial. Since chert is relatively rare in the Cenozoic carbonate sequence of the Arabian Platform, we consider it probable that the abundant chert clasts originated from the ophiolite suite at the Neotethys suture, ~200 km farther north (Fig. 1). The unidentifiable weathered clasts may thus be of igneous constituents from this ophiolite. The gravel thus indicates the presence of the ancestral River Euphrates in this area at ~9 Ma.

The disposition of the basalt and gravel indicates that the former cascaded into the Euphrates valley from the south, the evidence (Fig. 4b) suggesting that it reached beyond the terrace bluff of what was at this time a low terrace on the north side of the river. The basalt thus covered the contemporaneous river thalweg. This evidence is indeed similar to what is observed elsewhere, where basalt flows have interacted with river valleys (e.g., Westaway et al., 2004, 2006b; Maddy et al., 2005). By analogy, the Euphrates will have subsequently incised around the northern tip of the Shireen basalt flow.

We have been unable to identify clear palaeo-flow indicators (e.g., cross-bedding, clast imbrication) in the Shireen gravel. However, from the regional context we con-

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sider it likely that the Euphrates flowed eastward through this site at this time, adjusting from course 1 to course 2 in Fig. 2 as a result of the basalt-damming of this valley. This eastward course most likely led towards Raqqa, shown schematically as course 2 in Fig. 1. NW of Raqqa, a succession of fluvial sands and gravels, locally >10 m thick (base not exposed), attributed to the Euphrates from their polymict lithology (Table 2), crops out over an area of  $\sim 200 \text{ km}^2$  (Fig. 1) at up to  $\sim 320 \text{ m a.s.l.}$ ,  $\sim 80 \text{ m}$  above the modern river. These gravels adjoin the western end of the outcrop of Upper Fars Formation (Fig. 1), but like the basalt were inferred in the 1960s mapping to be “Early Pleistocene” (Ponikarov, 1966). These deposits appear much less weathered than those at Shireen, but the Raqqa area has much less annual rainfall ( $< 200 \text{ mm}$ , against  $\sim 350 \text{ mm}$ ) and the Pleistocene Euphrates terraces have locally experienced minimal weathering, in contrast with farther NW. We thus suggest that these Raqqa gravels mark the downstream limit of the SE course of the Euphrates through Shireen, recorded by the gravel there, and also delineate the paleocoastline adjoining the contemporaneous Late Miocene depocentre of the Upper Fars Formation. Subsequently, due to continuing regional uplift, the sea retreated from this area and the Euphrates thus extended downstream across eastern Syria and Iraq (3, Fig. 1).

Previous studies (e.g., Brew et al., 1997; Besançon and Geyer, 2003) have noted that the SE-trending course of the Euphrates below Raqqa is structurally controlled, by local downwarping along the Euphrates Fault Zone. We thus suggest that in the Late Miocene, the reach of the ancestral Euphrates between Shireen and Raqqa was also controlled by the same lineation (Fault F1 in Fig. 2). We infer that, at a later stage, processes in the Shireen area (including local faulting and folding, the latter including NW downthrow on fault F2; differential erosion; southward tilting) disrupted this course and deflected the river to form its modern looped course upstream of Raqqa, which is now flooded by the Lake Assad reservoir (Fig. 1).

Regarding the incision history, we note that in SE Turkey the +60 m Euphrates terrace (QfIII) has been thought to date from MIS 12 and, it seems, the volumetrically most significant gravel (of terrace QfV, reaching +110 m) as been thought to have fin-

ished aggrading in MIS 22 (Sanlaville, 2004; Demir et al., 2004). Taking account of the regional southward tapering in uplift rates (Arger et al., 2000), we suggest that the principal Euphrates gravel around Shireen (at +60 m, assigned to terrace QfIII; Figs. 2, 3) likewise probably aggraded no later than MIS 22. The minimal net incision in this area, from +70 m at ~8.9 Ma to +60 m estimated at ~0.9 Ma, is attributed in part to local downwarping (before ~4 Ma) caused by slip on fault F2 (Fig. 2) and in part to the dramatic downstream channel lengthening that occurred (Fig. 1). Maintaining a typical downstream channel gradient of  $\sim 0.3 \text{ m km}^{-1}$ , the ~800 km of channel-lengthening indicated would mean that incision by the Euphrates underestimated the contemporaneous regional uplift by ~240 m.

## 5 Conclusions

The discovery of Euphrates gravel, capped and preserved by basalt, dated to ~9 Ma, constrains the evolution of the River Euphrates in northern Syria during the Late Miocene. In the early Middle Miocene, the ancestral Euphrates reached the sea near Kahramanmaraş in southern Turkey (1, Fig. 1). Regional uplift in the Late Miocene caused the coast to retreat south and east, and the river thus lengthened downstream to the vicinity of Raqqa in northern Syria (2, Fig. 1). Continuing regional uplift in the Pliocene caused the coast to retreat farther southeast, and the river extended to the eastern margin of the modern Arabian Platform uplands (3, Fig. 1).

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**Table 1.** Euphrates terraces in the Shireen area.

Terrace	Height (m)	Description	MIS	Age (ka)	Rate (mm/a)
Qf0 [Q4]	+8	Fluvial sand/gravel	2	15	0.067
QfI [Q3]	+15	Fluvial sand/gravel	6	140	0.057
QfII [Q2]	+40	Fluvial sand/gravel	12	430	0.077
QfIII [Q1b]	+60	Fluvial sand/gravel	22	870	0.061
Shireen	+70	Fluvial sand/gravel		8900	0.007
QfIV	+85	Fluvial strath (?)	?	?	?
[Q1a]	+100	Subaerial weathering	–	–	–

After Oguchi (2001) and Sanlaville (2004), with our tentative age estimates. These inferred ages for the deposits forming terraces Qf0 and QfI are consistent with the results of Kuzucuoğlu et al. (2004) farther upstream in the Euphrates, at Birecik (Fig. 1). Notation in brackets is after Oguchi (2001). Incision rates are calculated relative to 7 m above modern low-stage (autumn) pre-dam river level. MIS denotes the marine oxygen isotope timescale.

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**Table 2.** Gravel composition near Khuzayma.

Lithology	Number	%
Quartzite	89	36%
Chert or flint	55	22%
Quartz	33	13%
Mafic igneous	32	13%
Limestone or marble	18	7%
Calcschist	10	4%
Hard mudstone	8	3%
Sandstone	2	1%

Summary of results of a stone count of 247 clasts in the 16–32 mm size fraction, collected from the Euphrates gravel at [DV 98374 96614], to the south of Khuzayma (Fig. 1).

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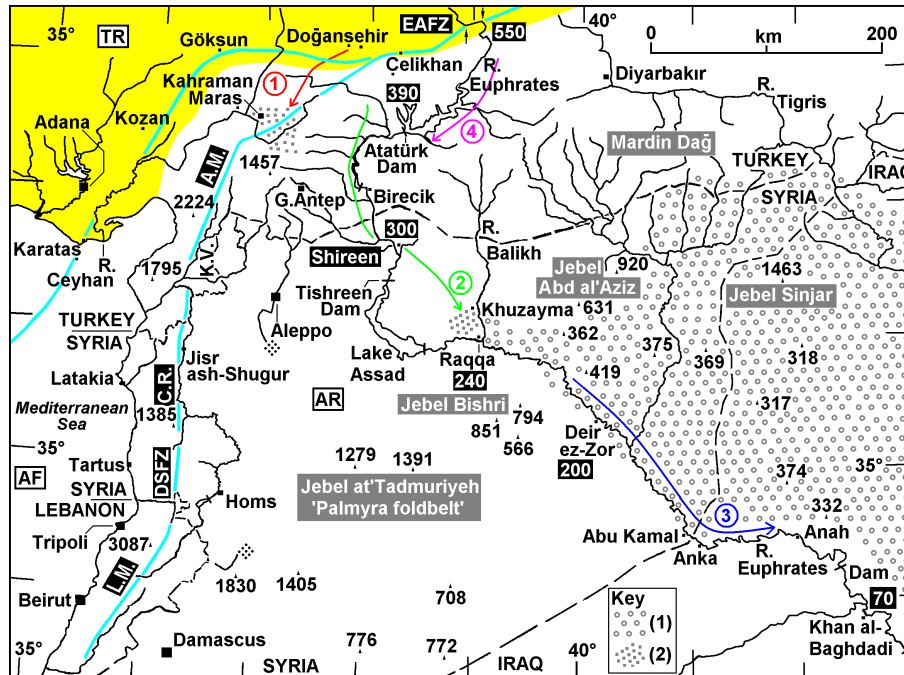


Fig. 1.

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**Fig. 1.** Map locating the study area in relation to the River Euphrates (with its altitude a.s.l. marked at key sites) and the active left-lateral faults (after Westaway, 2004, coloured light blue) bounding the Arabian (AR), African (AF) and Turkish (TR) plates. Mountain ranges forming by distributed shortening along the DSFZ are: L.M., Lebanon Mountains; C.R., Syrian Coastal Range (Jebel Nusayriyah); and A.M., Amanos Mountains. K.V. denotes the Karasu Valley. The Anatolian crustal province is shaded yellow, except where offshore. The suture of the Neotethys Ocean follows its southern margin, also marking the northern limit of the Arabian Platform. Ophiolitic rock (chert, basalt, etc.) from this suture zone and metamorphic rock (quartzite, calcschist, etc.) from Anatolia, farther north, are major constituents of the Euphrates gravels. Cenozoic folding, superimposed on regional uplift, has created the uplands within the Arabian Platform labelled in grey. In the Key, (1) denotes outcrop of the Upper Fars Formation; (2) denotes concentrations of stacked fluvial sand and gravel, from the early Middle Miocene and (?) Late Miocene. In the figure, 1, 2, 3 and 4 indicate the Euphrates in the Middle Miocene, Late Miocene, Pliocene, and Pleistocene, respectively coloured red, green, dark blue and purple. 1, 3 and 4 are from previous work; 2 is inferred in this study.

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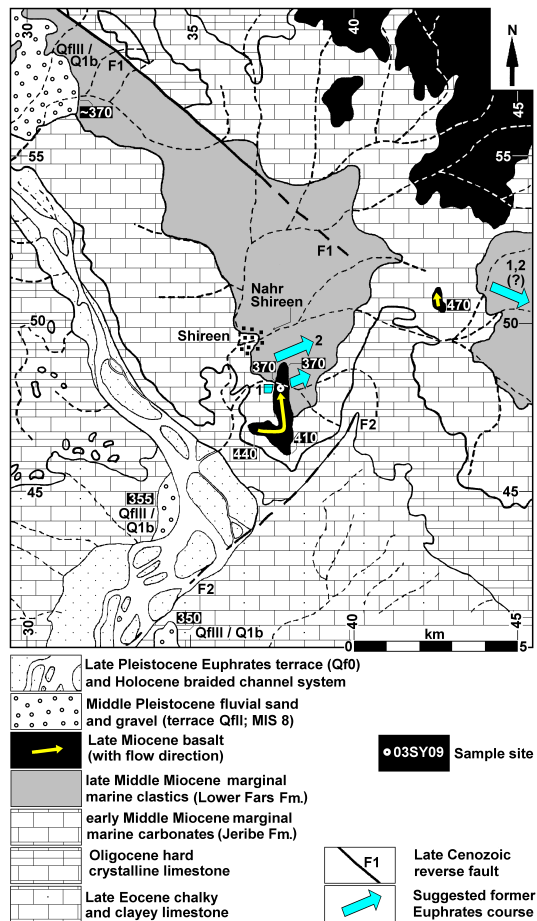


Fig. 2.

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**Fig. 2.** Geological map of the Shireen area, after Ponikarov (1966), as modified by Oguchi (2001), showing the location of basalt sample 03SY09. The underlying fluvial gravel was not recognised in this mapping, presumably because the modern quarry had not yet opened. 1 indicates the inferred course of the Euphrates before this basalt eruption; 2 indicates how we suggest it adjusted immediately afterward. The Euphrates was locally ~300 m a.s.l.; construction of the Tishreen Dam in the 1990s has impounded it at ~325 m (see Fig. S2 in the online supplement (<http://www.electronic-earth-discuss.net/1/167/2006/eed-1-167-2006-supplement.zip>) for more detail). Shireen is an abbreviated phonetic spelling of the name of the village in our study area. Alternative spellings, in full, transliterated from Arabic on maps and other publications, include Shirrin esh-Shemaliyeh, Shirrin ash-Shamaliyah, Serrin Esh-Shamaligeh, Surrien Shamali, and Sarine Shamali.

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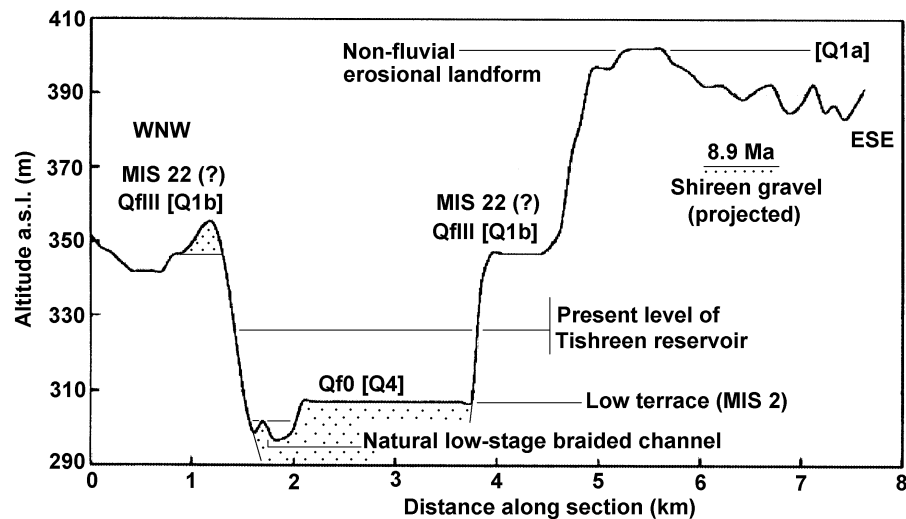
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**Fig. 3.** Cross-section through the Euphrates terrace staircase, ~4 km south of Shireen, after Oguchi (2001) (cf. Table 1).

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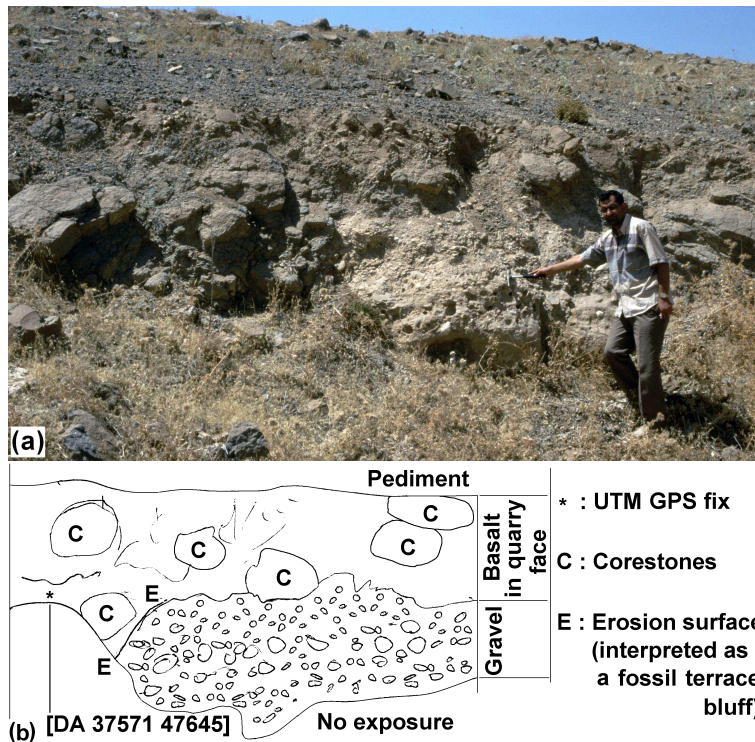
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**Fig. 4.** (a) Field photograph, looking west at the Shireen quarry exposure of gravel and overlying basalt. T. Demir provides scale. (b) Field sketch of this exposure.

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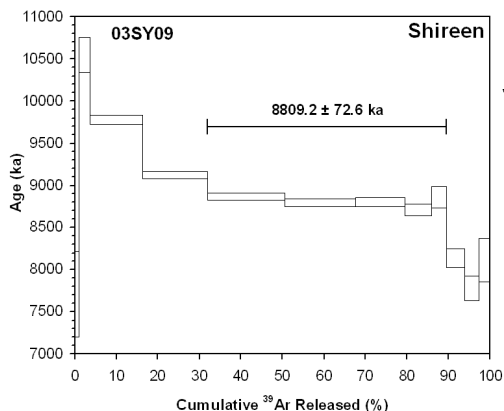
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Weighted plateau age:  $8809.2 \pm 72.6$  ka

Total fusion age:  $8936.6 \pm 57.7$  ka

Normal isochron age:  $8838.0 \pm 115.8$  ka

Inverse isochron age:  $8826.9 \pm 114.1$  ka

Mean squared weighted deviation: 3.98

**Fig. 5.** Main part of figure shows an age spectrum derived from step-heating of sample 03SY09. The horizontal bar indicates the heating steps used to calculate the age estimate from step-heating. To the right are listed four age determinations for the same sample based on different analysis methods. The calculation based on step-heating is considered definitive. Calibration utilised the U.S. Geological Survey Taylor Creek Rhyolite sanidine standard TCR-2A with an age of 28.34 Ma. The material dated was groundmass, after magnetic separation, prepared following the procedure used previously by Yurtmen et al. (2002) and Westaway et al. (2004, 2005b, 2006b). Analysis was carried out at the Isotope Geosciences Laboratory, Massachusetts Institute of Technology, the method used being essentially the same as that described by Harford et al. (2002).

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