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Dear Sir/Madam

JQSR-D-16-00142

I am resubmitting our paper for the FLAG special issue od QSR:

River terrace development in the NE Mediterranean region (Syria and Turkey): patterns in relation to crustal type

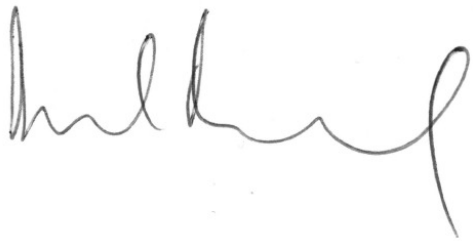
Please note tat the title has been changed to reflect the main thrust of the revision, which, based on advice from the reviewers and from the Guest Editor, gives emphasis to the patterns of archive preservation in relation to crustal type.

The resubmission includes a 'response to reviews' document and a colour-coded annotated version of te new text, as well as a clean copy.

I hope that this will prove acceptable.

Many thanks

Yours faithfully



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River terrace development in the NE Mediterranean region (Syria and Turkey): patterns in relation to crustal type

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[Abstract]
It is widely recognized that the optimal development of river terraces globally has been in the temperate latitudes, with NW and Central Europe being areas of particular importance for the preservation of such archives of Quaternary environmental change. There is also a growing consensus that the principal drivers of terrace formation have been climatic fluctuation against a background of progressive (but variable) uplift. Nonetheless river terraces are widely preserved in the Mediterranean region, where they have often been attributed to the effects of neotectonic activity, with a continuing debate about the relative significance of fluctuating temperature (glacials–interglacials) and precipitation (pluvials–interpluvials). Research in Syria and southern–central Turkey (specifically in the valleys of the Tigris and Ceyhan in Turkey, the Kebir in Syria and the trans-border rivers Orontes and Euphrates) has underlined the importance of uplift rates in dictating the preservation pattern of fluvial archives and has revealed different patterns that can be related to crustal type. The NE Mediterranean coastal region has experienced unusually rapid uplift in the Late Quaternary. The relation between the Kebir terraces and the staircase of interglacial raised beaches preserved along the Mediterranean coastline of NW Syria reinforces previous conclusions that the emplacement of the fluvial terrace deposits in the Mediterranean has occurred during colder climatic episodes.

Keywords: River terraces; Uplift; Climatic forcing; Crustal type; Euphrates; Orontes

Highlights

Climatic fluctuation has forced river-terrace formation in the Mediterranean region

Climatic forcing has been over-printed onto the effects of background regional uplift

Differing patterns of fluvial-archive preservation reflect distinct uplift histories

Disparate uplift histories correlate with crustal type and mobility of lower crust

The effects of Quaternary tectonic activity are seen in the deformation of terraces

1. Introduction

River terraces occur in most parts of the world (Bridgland and Westaway, 2008a, b, 2014) and are common throughout the Mediterranean region (Fig. 1), being found in southern Europe (Harvey and Wells, 1987; Karner and Marra, 1998; Schoorl and Veldkamp, 2003; Stokes and Mather, 2003; Santisteban and Schulte, 2007; Meikle et al., 2010; Candy et al., 2004; Cunha et al., 2005, 2008; Zagorchev, 2007; Martins et al., 2010; Viveen et al., 2012a, b, 2013), Turkey (Demir et al., 2004; Westaway et al., 2004, 2006a; Maddy et al., 2005, 2007, 2008, 2012a), Syria (Besançon et al., 1978; Besançon and Sanlaville, 1984), Egypt (Said, 1993; Zaki, 2007; Woodward et al., 2015) and Morocco (Aït Hssaine and Bridgland, 2009; Westaway et al., 2009a). It is widely agreed that such terraces have formed in response to latest Cenozoic uplift (Van den Berg, 1994; Maddy, 1997; Antoine et al., 2000; Maddy et al., 2000, 2001; Bridgland, 2000; Van den Berg and van Hoof, 2001; Westaway, 2002a; Starkel, 2003), with an equally prevalent view that the triggering of the different fluvial activity that has led to terrace formation (essentially an alternation of down-cutting and aggradation) has been related to Quaternary climatic fluctuation, typically (but not invariably) at a glacial–interglacial frequency (for recent inter-regional reviews, see Bridgland and Westaway, 2012, 2014). While most workers have envisaged the uplift responsible for the widespread phenomenon of river terraces to be regional, epeirogenic and 'atectonic', rather than caused by plate-tectonic processes or contemporaneous fault movement (cf. Maddy et al., 2000), some have made a case for the involvement of 'active tectonics'; in the Mediterranean region these include Mather et al. (1995) and Stokes and Mather (2000, 2003), in the fault-bounded basins of southern Spain, and Boulton and Whittaker (2009) in the lowermost Orontes (Asi), Hatay Province, Turkey (see below; Fig. 2). Westaway (2002a), who has strongly advocated regional uplift as a principal control on river terrace formation, has demonstrated that the relative spacing of such terraces can be used as an indication of the strength and rapidity of the uplift. This approach has shown that uplift accelerated markedly, generally from a very low or non-existent rate, in the late Pliocene and again at the start of the Middle Pleistocene (following the Mid Pleistocene Revolution, when the 100 kyrs climatic cycles began), suggesting that the increasing severity of cold (glacial) climate cycles was an important influence, through coupling between climatic variation and Earth surface processes (Westaway, 2002a; Bridgland and Westaway, 2008a, b, 2014; Westaway et al., 2009b).

Westaway (2002a, 2006) has suggested compensation within the mobile lower continental crust as the most likely mechanism for sustaining the observed progressive regional uplift; this is envisaged as a long-term isostatic effect of the redistribution of material by erosion and sedimentation, but, unlike with glacio-isostasy, the effect is generally permanent (cf. Bridgland and Westaway, 2012, 2014). Thus lower crust has been squeezed from areas subsiding under the weight of sediment and has accumulated beneath uplifting areas, maintaining their additional elevation and providing important positive feedback in support of the isostatic effect. This mechanism cannot operate in areas where the lower crust is not mobile, as in Archaean cratons, in which the crust has cooled and solidified throughout its depth. Indeed, the observed absence of terrace sequences in such areas would seem to corroborate the envisaged mechanism, in the absence of any other explanation for such patterns of terrace occurrence (cf., Westaway et al., 2003; Bridgland and Westaway, 2008a, b, 2014; Westaway et al., 2009b). Thus the characteristic river terrace staircases observed in

areas such as NW Europe have formed on relatively hot, dynamic Phanerozoic crust. It has also been shown that rivers on crust of an antiquity intermediate between Archaean and Phanerozoic (i.e., Proterozoic), which generally has a limited thickness of mobile lower crust, have produced fluctuating patterns of terrace formation and accumulation, suggesting oscillations between uplift and subsidence (Westaway, 2012; Bridgland and Westaway, 2014; Westaway and Bridgland, 2014).

1.1 Patterns of fluvial archive preservation

Four main patterns of sedimentary fluvial archive preservation have been recognized thus far from the various surveys undertaken under the auspices of the Fluvial Archives Group, including successive International Geoscience (IGCP) projects: IGCP 449 (Bridgland et al., 2007a) and IGCP 518 (Westaway et al., 2009b). These preservation types are as follows: (1) typical terrace staircase archives on dynamic (Phanerozoic) crust with a mobile lower layer, (2) stacked sequences in subsiding areas, in which accumulation of sediment is a significant positive-feedback driver of the subsidence, (3) sequences in ultra-stable cratonic regions (coincident with Archaean crustal provinces), which (as noted above) show evidence for neither uplift nor subsidence, but instead for the lateral accretion of sediments of different ages (Westaway et al., 2003; Bridgland and Westaway, 2014), and (4) records intermediate between patterns 1 and 3, showing alternations of uplift and subsidence, as seen in areas with thin mobile crustal layers, often of Proterozoic age (Westaway, 2012; Bridgland and Westaway, 2014; Westaway and Bridgland, 2014; see above). The preservation patterns within archive type 1 are divisible into systems that have formed terraces in approximate synchrony with glacial–interglacial climatic fluctuation, those that have formed terraces less often than that and those (rare) systems in which terrace formation has occurred more frequently than once per glacial–interglacial cycle (Bridgland and Westaway, 2008a).

At no great distance from the NE Mediterranean is an area that has yielded a wealth of fluvial archive data, highly influential in the recognition of the above patterns: the northern Black Sea region. This area is dominated by three important southward-draining rivers: in a west–east direction, the Dniester, Dnieper and Don (Fig. 3). The records from these rivers were synthesized by Matoshko et al. (2004) and further reviewed by Bridgland and Westaway (2008a, 2014), with detail of the prevailing crustal properties and their relation to the fluvial archives was further discussed by Westaway and Bridgland (2014). All three rivers have excellent fluvial archives, benefitting from research over very many years and well constrained by biostratigraphy, loess–soils overburden sequences and geochronology (Matoshko et al., 2004). Despite their relative proximity to each other (Fig. 3A), particularly in terms of global regions and climatic zonation, the sedimentary sequences of these three rivers have markedly contrasting geometries, an observation that can be matched closely with the crustal province in which their valleys are developed. Thus the Dniester, the furthest west, and flowing over through the SW part of the Dniester–Bug crustal domain (Fig. 3A), has formed a conventional terrace staircase in a valley that has been incised into Miocene basin-fill deposits, ‘basin inversion’ (the start of incision) having occurred at around the beginning of the Pliocene. As Fig. 3B shows, several broad Pliocene terrace formations are preserved, as well as three classified as Lower Pleistocene, after which the river increased the steepness of its incision into the basin fill at around the Mid-Pleistocene Revolution (MPR), when the change to 100 ka interglacial–glacial climatic cycles took place

(Mudelsee et al., 1997; McCymont et al., 2008). Subsequent to this change in the pattern of climatic change, the Dniester has formed a lower staircase of terraces at approximately one per 100 kyr cycle. The overall incision pattern recorded by the Dniester is thus regarded as a response to uplift, which showed comparable changes in reaction to enhanced surface processes resulting from the climatic cooling in the late Pliocene and then again with the onset of the longer climatic cycles, with greater severity of glacials,at the MPR (Westaway, 2002a, b).

The River Dnieper, in contrast to the Dniester, flows on the cratonic crust of the Ukrainian Shield (Fig. 3A). Its sedimentary archives date back to the Miocene but show no evidence of consistent uplift since that time, there having been no progressive incision by the river. Instead the deposits occur laterally distributed over a wide area within a range of a few tens of metres above or below the modern Dnieper (Fig, 3C). This, then, provides an excellent example of the cratonic pattern of fluvial archive preservation noted above. Finally the Don, which flows over the Early Proterozoic crust of the Voronezh Shield or the Lipetsk–Losev crustal domain (Fig. 3A), has an archive of Late Cenozoic sediments that differs yet again in its preservation pattern, with evidence that the valley has experienced periods of uplift interspersed with subsidence. Thus uplift is indicated by the oldest suite of (partly buried) Don terraces, formed during the late Miocene–Pliocene (Fig. 3D). In the Early Pleistocene there were alternating shorter periods of uplift and subsidence, culminating in the aggradation of a continuous sequence representing much of the Middle Pleistocene, following which, from MIS 8 onwards, there has been further uplift and terrace formation (Fig. 3D). This, then, is an example of preservation pattern 4 (see above).

Figs 1–3 hereabouts

1.2 Consideration of other potential mechanisms for terrace generation

The role of sea-level fluctuation as a driver for terrace formation, via its causal linkage with base-level change, has also been promoted by many workers (cf. Törnqvist and Blum, 1998; Tucker and Whipple, 2002), irrespective of crustal movements. In the Mediterranean region (albeit on the Atlantic seaboard) a convincing case has been made for glacial–interglacial eustatic change as a mechanism for terrace generation in Portugal (Martins et al., 2010; Viveen et al., 2013), where the continental shelf is narrow and sea-level change might be expected to exert a significant influence in lower fluvial reaches onshore. This mechanism has also been envisaged as a key driver for aggradation in the Tiber system, Italy (Karner and Marra, 1998), although this latter study did not consider the alternative possibility of a climatic driver. Such base-level forcing is generally envisaged to lead to progressive vertical incision by rivers from their downstream end, by the mechanism of knick-point recession (Whipple and Tucker, 1999, 2002; Roberts and White 2010; cf. Bridgland and Westaway, 2012); for a full review of this approach, and an attempt to reconcile it with evidence from river terrace sequences, see Demoulin et al., this issue).

In the warm-temperate Mediterranean climatic zone there has also been debate about whether Quaternary cycles of varying temperature (glacials–interglacials) have been important drivers of fluvial activity, as is supposed in NW Europe (e.g., Antoine et al., 2000; Bridgland, 2000), or whether humidity cycles (pluvials–interpluvials) have been more

important. Humidity fluctuations have been invoked as an important influence on rivers in the eastern Mediterranean, where they might be linked to the fluctuating strength of the Indian Ocean monsoon (e.g., Rossignol-Strick, 1985; Kroon et al., 1998), although much of the evidence is from recent timescales. Conversely Macklin et al. (2002) have compiled evidence from the last two climate cycles and found that temperature is likely to be the most important driver, as it is further north in Europe.

Working in the Gediz River system in western Turkey, which has abundant fluvial archives but has been disrupted by Late Cenozoic – Quaternary volcanism, Veldkamp et al. (2015) found evidence to support climatic forcing of river terrace formation in the Early Pleistocene. This evidence took the form of a sequence of rubified palaeosols and laminated calcretes formed at the top of fluvial (Gediz) sediments and within colluvial overburden. From micro-morphological and stable-isotope analysis they concluded that rubified soils had formed in a warm, moist and forested environment, whereas the calcretes recorded cooler and drier periods with an open (non-wooded) landscape. They inferred that the colluvial sediments represented colder periods of landscape instability, during which fluvial incision might have occurred, thus suggesting down-cutting at cooling transitions in this system. From the Ar–Ar age of a capping lava (~1.3 Ma) they suggested a tentative correlation between the formation of the various Gediz terraces and major climatic transitions during the late Early Pleistocene.

The present paper will review evidence from work carried out by the authors in Syrian and southern Turkish river systems that has a bearing of these various debates and further suggests a strong linkage between patterns of fluvial archive preservation and crustal type. The text will be organized according to crustal provinces.

2. Fluvial records from the northern Arabian platform

The crust of the northern Arabian Platform is of Late Proterozoic age, having consolidated during the latest Precambrian 'Pan-African' orogeny. However, it shares a characteristic with older Proterozoic crust elsewhere, in that it consists of a thick basal mafic layer overlain by a relatively thin layer of mobile felsic lower crust (cf. Demir et al., 2007a). Representing a separate tectonic plate, it is bounded to the west by the Dead Sea Fault Zone (DSFZ), which separates it from the African Plate, and to the north by the East Anatolian Fault Zone, which marks its separation from the Turkish Plate (Fig. 2). The northern Arabian Platform is drained southwards to the Persian Gulf by the twin rivers of Mesopotamia, the Tigris (Dicli) and Euphrates (Firat), while its western fringe is drained northwards by the Orontes, which follows the DSFZ for much of its course (Fig. 2).

2.1. The River Euphrates in Turkey and Syria

The fluvial record of the Euphrates has been studied by the authors in both Turkey and Syria (Demir et al., 2007a, b, 2008, 2012; Abou Romieh et al., 2009); comparison can also be made with the sequence (downstream) in Iraq, based on studies there by Tyràček (1987). This system will be considered first, as it has a more central location within the Arabian Platform. In Syria geochronological constraint on the ages of Euphrates deposits has been provided by Ar–Ar dating of basalt lavas that cap terrace gravels between Raqqa and Deir ez-Zor (Demir et al., 2007b; Fig. 4). These basalts date from 2.717 ± 0.02, 2.116 ± 0.039 and

0.402 ± 0.011 Ma and seal gravels ~65, ~45 and ~8–9 m above the modern river, respectively. Previous work by Besançon and Geyer (2003) showed that the Pleistocene sequence of the Euphrates occupies a deep infilled palaeochannel incised well below the level of the modern valley (Fig. 4). The new basalt dates allowed key stages in the formation of this valley to be calibrated, leading to a revised interpretation (Demir et al., 2007b; Bridgland and Westaway, 2014) envisaging a greater age for much of the sequence.

Fig. 4 hereabouts.

The new interpretation recognizes relative landscape stability in the Syrian reach of the Euphrates prior to ~3 Ma, followed by a phase of fluvial incision, then further relative stability before renewed incision, starting at ~2 Ma, which saw the river cut the deep palaeovalley ~30 m below its present level (Fig. 4). A 40–45 m thickness of gravel accumulated, culminating at the level of terrace QfII (using the Besançon and Geyer (2003) scheme), ~23 m above modern river level, after which renewed incision began. This 'inversion' is dated by basalt ages in combination with uplift modelling (cf. Demir et al., 2007a) to around the start of the Middle Pleistocene. It may thus mark the response of the Euphrates system to the effects on fluvial processes of the MPR, and in particular the greater intensity of glacial episodes it brought about, previously suggested as a cause of increased incision in the Dniester (see above).

Further upstream, at Birecik, southern Turkey, the same palaeovalley has been recognized, but it is disposed significantly higher within the landscape (Fig. 5), its base ~5 m above modern floodplain level (Demir et al., 2008). Its fill, the Bilgin Gravel, reaches 56 m above the modern river and has a series of terraces cut into it, presumed to date from MIS 22–12, although this is largely by analogy with the dated sequence in Syria, as there is no available geochronology from the Turkish reach of the Euphrates. This correlation is, however, supported by the occurrence of comparable Acheulian artefacts in the fill sequences of both reaches (Demir et al., 2007a, 2008). Thus the same Early–Middle Pleistocene inversion is evident north of the Syrian–Turkey border, although there has been greater uplift there in the Middle–Late Pleistocene, raising the infilled palaeovalley significantly higher in the landscape and consistent with the general southward tilt of the northern Arabian platform observed previously (Arger et al., 2000).

Fig. 5 hereabouts

In the Birecik reach an older palaeovalley-fill has been recorded, between ~100 and ~140 m above the river. This comprises the İt Dağı and Hancağız gravels, the former attributed to the Euphrates on the basis of its polymict (Anatolian) clast composition and the latter a local limestone fan deposit (Demir et al., 2008; Fig. 5). These are thought, from their disposition within the landscape (both in relation to younger Euphrates deposits and by analogy with dated deposits in the Syrian reach of the Euphrates and in the Tigris in Turkey), to date from the Early–Mid Pliocene. Studies of the Euphrates sequence ~100 km further upstream, where the river is accessible from the Şanlıurfa to Adiyaman road at Karababa bridge, have revealed the same thick sedimentary sequences attributed to prolonged aggradation phases during the Early–Mid Pliocene and during the Early Pleistocene, although the preservation and thickness of these deposits is strongly influenced by active folding thereabouts (Demir

et al., 2012). These are the Işık and Kavşut gravels, respectively. The former is associated with Pliocene coastal regression, which led to the mouth of the Euphrates migrating many hundreds of kilometres south-eastward (from north-central Syria probably as far as central Iraq), and concomitant aggradation, even though the landscape in this part of Turkey was uplifting. The Kavşut gravel is attributed to regional subsidence during the Early Pleistocene (cf. Demir et al., 2012). Once again the correlation of the thick Lower Pleistocene Kavşut Gravel at Karababa with the Bilgin Gravel at Birecik and with the equivalent palaeovalley-fill deposits in the Syrian reach of the Euphrates is supported by the recovery of Lower Palaeolithic artefacts from the first-mentioned deposits in gravel quarries in the vicinity of Karababa bridge. Note that the above interpretation includes consideration of changes in the length of the system (i.e. downstream distance to the sea, or base level), rather than an uncritical formula that simply translates elevation to age, in relation to uplift.

The suggested ages of the terraces in the Turkish and Syrian reaches of the Euphrates are largely based on uplift modelling, using the technique of Westaway (2002b, 2007), with important calibration from the basalt dates in Syria (see above). Like many rivers globally, the Euphrates, in its Syrian reach, would appear to have generated terraces during only the most extreme climatic cycles, broadly equivalent to the 'supercycles' of Kukla (2005): MIS 22, 16, 12, 6, 2 (Fig. 4). A comparable sequence can be seen in Kukla's (1975, 1977) central European record from the River Svratka, Czech Republic. The reversals in the direction of vertical crustal movement evident from the Euphrates archive are comparable with those observed in the record of the Don (compare Figs 4 and 5 with Fig. 3D). Both rivers are flowing over crust with a restricted thickness of mobile layer; in the Arabian platform this has been caused by mafic underplating during the aforementioned Pan-African Orogeny.

2.2. The River Tigris in southern Turkey

The Tigris sequence has been studied in the area around and downstream of Diyarbakır (Bridgland et al., 2007b; Westaway et al, 2009c), near the northern margin of the Arabian Platform. The dating of the terrace sequence in this upper part of the Tigris has been facilitated by the interbedding of fluvial deposits with basaltic lava periodically erupted from the large Karacadağ shield volcano centred ~50 km SW of Diyarbakır. At least nine Tigris terraces have been identified (Westaway et al, 2009c; Bridgland and Westaway, 2014; Fig. 6), the highest, ~200 m above present river level, marking the switch from stacked accumulation of fluvial deposits to valley incision (basin inversion), which occurred between the mid Late Miocene and the Middle Pliocene. Widespread gravel ~60–70 m above the Tigris floodplain crops out on both sides of the valley at Diyarbakır, including beneath the basalt city walls. Dated basalts overlying this terrace have proved to represent multiple flows, implying a span of at least 150 ka during which there was no valley deepening: K–Ar/Ar–Ar dates of 1.22 ± 0.02, 1.19 ± 19 and 1.07 ± 0.03 Ma have been obtained from basalts at this level, with the distinction corroborated by different magnetic polarities in basalts on the two sides of the valley (Westaway et al, 2009c; Bridgland and Westaway, 2014; Fig. 6). It is uncertain whether the river was temporarily ponded by any of these lava flows, since no lacustrine sediments, such as have been recorded in the Gediz, in western Turkey (Maddy et al., 2012b, this issue), have been observed in the Diyarbakır reach of the Tigris.

Fig. 6 hereabouts

Lower terraces record the Middle–Late Pleistocene incision by the Tigris through this basalt, forming the narrow incised valley of the modern river, perhaps responding to an acceleration (or re-commencement) of uplift following the MPR (see above). The dating of these lower terraces is further constrained by a younger dated basalt, erupted at 0.43 ± 0.02 Ma (MIS 12), capping gravel ~21–22 m above the modern river (Westaway et al, 2009c; Bridgland and Westaway, 2014; Fig. 6). The application of numerical modelling as a means of obtaining approximate ages for the terrace gravels, using the dated basalts for calibration, suggests a similar Middle Pleistocene record to that in the Euphrates, with only some glacial–interglacial climate cycles represented by terraces (these being fitted to likely isostope stages based on their relative height within the landscape: Fig. 6). The pattern of the modelled uplift history here is compatible with a thin mobile lower-crustal layer (~5–7 km thick), consistent with the known presence of the aforementioned thick layer of mafic underplating at the base of the crust beneath the Arabian Platform (Westaway, 2012; Westaway and Bridgland, 2014). In contrast with the Euphrates, and indeed with the Don (see above), the history of vertical crustal movement indicated by the Tigris sequence (Fig. 6) would appear to be a fluctuation between uplift and stability, rather than uplift and subsidence, suggesting transitional crustal properties, perhaps. The early Middle Pleistocene rate of incision, and thus of uplift, was relatively high, however: ~0.1 mm a^{-1} (Westaway et al., 2009c), with evident slowing of uplift since ~MIS 12, which is represented by a terrace relatively close to the valley floor, its age fixed from a lava date (Fig. 6).

2.3. The River Orontes in Syria

The Orontes has been studied by the authors from near the Lebanon border in western Syria to the Mediterranean SW of the Turkish city of Antakya (Bridgland et al., 2012). A notable feature of its Quaternary record is that this varies considerably between different crustal blocks, the river flowing through two subsiding pull-apart basins within the DSFZ in which stacked sedimentation has taken place throughout the Quaternary and no terraces occur (Fig. 7). There are also three gorge reaches that lack terraces, despite being located on uplifting crust, resistant rocks in these reaches having prevented the lateral migration required for terrace formation (cf. Bridgland and Westaway, 2008a, 2012; Fig. 7).

Fig. 7 hereabouts:

On the eastern flank of the Upper Orontes, upstream of Homs, is preserved an extensive staircase of calcareously cemented Late Cenozoic terraces (Bridgland et al., 2003, 2012; Fig. 8A). Initial attempts to construct an age model for these terraces used upstream projection from a fossiliferous site in the Middle Orontes, at Latamneh, supposing that site to represent an age close to MIS 12 (based on a mixture of early Middle and late Middle Pleistocene mammalian species (Bridgland et al., 2003). Subsequent re-evaluation of the vertebrate evidence from Latamneh has suggested that it is much older; this, coupled with U-series dating of the Arjun terrace to MIS 6, led Bridgland et al. (2012) to propose the revised age model depicted in Fig. 8A. This allocates a terrace tread to every glacial–interglacial cycle following the MPR. The ages of the oldest terraces can only be approximate, but there is an upper limit provided by the ‘bedrock’ here, which is lacustrine

marl representing a basin filling that culminated in the early Pliocene, with inversion occurring, seemingly, before the beginning of the Pleistocene, perhaps related to the late Pliocene global cooling (see above). The lake had existed since the latest Miocene, when the Homs basalt (Ar–Ar dated ~6–4Ma: Searle et al., 2010; Westaway, 2011) was erupted into it (cf. Bridgland et al., 2012).

Fig. 8 hereabouts:

The Homs Basalt gives rise the first of the three gorge reaches along the course of the Orontes, the Rastan Gorge, separating the Upper from the Middle section of the valley (Fig. 7). In the Middle Orontes there is again a well-developed terrace record, newly discovered to extend up the eastern valley side to ~120 m above the modern river, these higher levels (marked by calcreted gravels comparable with those in the Upper Orontes) perhaps representing the Pliocene (Bridgland et al., 2012). The biostratigraphical marker at Latamneh would now be assigned an age in the region of 1.2–0.9 Ma, largely based on small-mammal faunas, interpreted in comparison with the Israeli sites at Ubeidiya and Gesher Benot Yaaqov, which are regarded as older and younger, repectively, than Latamneh (Bar-Yosef and Belmaker, 2010; Bridgland et al., 2012; cf. von Koenigswald et al., 1992; Mein and Besançon, 1993; Goren-Inbar et al., 2000). An important point of contrast with the Upper Orontes is the considerable thickness of the sediments at Latamneh: ~25 m. Given that this sequence is now attributed to the Lower Pleistocene, and that the lower-level terraces essentially appear to represent 100 kyr cycles within the late Middle and Late Pleistocene (based on the uplift modelling presented by Bridgland et al (2003), which remains valid: Fig. 8B), a comparison can be made with the sequence in the Euphrates, where thick Lower Pleistocene accumulations were inverted and incised following the MPR (Figs 4 and 5). It is possible that early Middle Pleistocene incision levels (terraces) within the vertical range of the Latamneh deposits have yet to be resolved.

Caution should applied when interpreting the evidence from Latamneh, however, since the locality lies within ~5 km of a dip-slip fault at Sheizar, which marks the eastern side of the subsiding Ghab Basin (Fig. 7) and has clearly been highly active throughout the Quaternary: its minimum Late Cenozoic vertical displacement, calculated from the depth of stacked sediments on its downstream side added to the height of the uppermost terrace deposits in the area upstream, is ~300m. A further complexity is that a tooth of the ancestral mammoth *Mammuthus meridionalis* was found at Sharia (Van Liere and Hooijer, 1961), now within the eastern outskirts of Hama, in deposits that fall within the range of altitude (relative to the valley-floor) of the Latamneh deposits. The Sharia fossil would seem to pre-date the Latamneh assemblage, which includes teeth of the more evolved mammoth *Mammuthus trogontherii* (Bridgland et al., 2012), although it could also belong within an Early Pleistocene aggradational sequence.

Thus the Middle Orontes sequence might have much in common with that in the Euphrates, representing another example of the accumulation–inversion sequence that characterizes fluvial archives from the Arabian Platform. It might be significant that in this reach the river wanders eastwards further onto the Arabian plate (and away from the DSFZ) than other parts of its course (Fig. 2), perhaps explaining why a sequence reminiscent of those on the Arabian Platform is found here. No evidence of this type of record is seen in the Upper

Orontes; the uppermost terraces there, attributed to the late Pliocene and Early Pleistocene (Fig. 8A), were determined from conglomerate outcrops separated by exposures of bedrock marl, indicating that discrete terrace treads are represented.

3. Fluvial records from the young, dynamic crust of the Latakia–Osmaniye area

In the area west of the DSFZ, including the coastal part of NW Syria and the Turkish regions of Hatay and the İskenderun Gulf (Fig. 2) the crustal properties reflect the typical geology of the Mediterranean region, resulting from its Cenozoic deformation in response to the subduction of the Tethys Ocean and the convergence of the African and Eurasian plates. (e.g., Aktaş and Robertson, 1984; Allen and Armstrong, 2008; Seyrek et al., 2014). Such crust, seen already in those reaches of the Orontes that flow close to the DSFZ (see above, especially the Upper Orontes), is considerably more dynamic than that of the Arabian Platform.

3.1. The Lower Orontes

Continuing the story of the Orontes, the river traverses the subsiding Ghab Basin and flows through its second gorge reach, the Darkush Gorge, cut through resistant Palaeogene limestone, which has again minimized lateral migration and prevented terrace formation (see above; Fig. 7). North of this gorge it flows into Turkey and into the second subsiding pull-apart basin, the Amik Basin (for recent discussion, see Seyrek et al., 2014), the flat surface of which forms the Antakya (Antioch) Plain (Fig. 7). Between Antakya and the Mediterranean the lowermost Orontes has contrasting terraced and gorge reaches, both indicative of uplift. Indeed, the river here flows through a coastal region, extending from Latakia (Syria) in the south to the Lower River Ceyhan in the north, near Osmaniye, that can be shown to have experienced very rapid late Quaternary uplift (Bridgland et al., 2012; Bridgland and Westaway, 2014). The Lower Orontes terraces, mapped in some detail by Erol (1963), were shown by Bridgland et al. (2012) to be formed by gravels containing mostly crystalline rocks from the Hatay ophiolite and the Precambrian–Palaeozoic succession exposed in the Amanos Mountains, to the NE. The even spacing of the five documented terraces (the lowest is too low to be shown in Fig. 7) is suggestive of regular formation in synchrony with 100 kyr climatic cycles, leading Bridgland et al. (2012) to suggest correlation with MIS 12, 10, 8, 6 and 2. Calculation of uplift rates on that basis approaches 2 mm a^{-1}, a rate far greater than in the higher parts of the Orontes valley in Syria (see above).

The last of the three Orontes gorges, cut into resistant latest Cretaceous ophiolitic rocks, is entrenched by 400 m (Fig. 7). It ends abruptly at an escarpment that is thought to coincide with an active dip-slip fault (Tolun and Erentöz, 1962; Erol, 1963; Boulton and Whittaker, 2009; Bridgland and Westaway, 2014). Erol (1963) also documented marine terraces bordering the Mediterranean coastline and provided tentative ages for these that were used by Seyrek et al. (2008) to infer a rapid uplift rate of ~0.1–0.2 mm a^{-1} during the latest Middle Pleistocene and Late Pleistocene, in reasonable agreement with the estimate from the Lower Orontes terraces (see above).

3.2. The Lower River Ceyhan, in the area of Osmaniye, southern Turkey

If the rapidity of uplift in the Lower Orontes requires estimation and inference, that indicated by the sequence in the River Ceyhan, ~50 km to the north, is well constrained by Quaternary basaltic lava that overlies fluvial levels down to the 4th terrace (of seven), ~90 m above floodplain level, which has an Ar–Ar age of 278 ± 7 ka, placing its eruption within MIS 9 (Seyrek at al., 2008). The three lower terraces, well spaced in terms of relative height, are thus attributable to MIS 8, 6 and 2 (Fig. 9). These data have provided an uplift rate for the late Middle and Late Pleistocene of 0.25–0.4 mm a^{-1}, increasing upstream (based on heights above the valley floor of well-dated terraces), perhaps in association with movement of the active fault that has uplifted the Amanos Mountains in this part of the northern DSFZ (Seyrek at al., 2008). This work has also elucidated the sequence of earlier terraces, partly preserved within an abandoned reach from which the river was probably diverted as a result of the basalt eruption (Fig. 9). Further upstream, the Ceyhan has cut a substantial gorge, up to ~2000 m deep, through the northern Amanos Mountains, the maximum age for the initiation of incision being the start of the fault movement, ~3.7 Ma (Westaway et al., 2006b), implying an average rate of down-cutting of ~0.54 mm a^{-1}, higher than the range calculated from the lower-level river terraces (see above). As Seyrek et al (2014) have established, this gorge reach of the Ceyhan is in the footwall (upthrown side) of an active normal fault, whereas the terraced reach further downstream is in its hanging (downthrown) wall, all of which is entirely consistent with the aforementioned differential uplift rates.

Fig. 9 hereabouts

3.3. The Nahr el Kebir, NW Syria

The third river draining through this zone of rapid-uplift is the Nahr el Kebir, which debouches into the Mediterranean at Latakia, its terraces interwoven with a sequence of upper Middle–Upper Pleistocene raised beaches (Copeland and Hours, 1978; Sanlaville, 1979; Devyatkin et al., 1996; Bridgland et al., 2008; Bridgland and Westaway, 2014). Considerable research has been undertaken on the Kebir terraces, largely because of their association with Palaeolithic artefacts (e.g., Copeland and Hours, 1979; Hours, 1981, 1994; Besançon et al., 1988). In summary of much work in the late 20th Century, Sanlaville (1979) attributed the fluvial terraces of the Kebir to Pleistocene cold stages (glacials) and the coastal marine terraces to interglacials. Recent work by the authors (Bridgland et al., 2008; Fig. 10) has found that the Sanlaville terrace scheme in the Kebir valley requires revision but has upheld their interpretation as cold-stage deposits, which interdigitate, rather than coalesce, with the raised marine terraces (Fig. 9A). The latter can also be confirmed as raised beaches from their bedding characteristics and patchily preserved molluscan fossils (cf. Devyatkin et al., 1996). These observations provide important corroboration of the view, from Macklin et al. (2002) amongst others, that river terrace formation in the Mediterranean region has been driven by cyclic temperature fluctuation rather than humidity cycles, although it is uncertain whether this is via a direct influence on fluvial activity and slope stability, as envisaged for systems in NW Europe (cf. Maddy, 1997; Bridgland 2000), or through the eustatic control of base level, as posited for Portuguese rivers (see above).

Fig. 10 hereabouts

Whereas the Sanlaville (1979) terrace scheme envisaged four terraces diverging downstream, the revised interpretation (depicted in Fig. 10B) shows four broadly parallel terraces, all significantly steeper than the modern floodplain. One of the Sanlaville terraces has been deleted from the scheme, since it can be shown to consist only of erosional remnants of slope deposits (Fig. 10A), but an additional formation has been identified just above the modern floodplain, from exposures in recent quarry workings. Bridgland et al. (2008) suggested that the four recorded terraces were formed in synchrony with the last four 100 kyr (glacial–interglacial) climate cycles, thus representing MIS 10, 8, 6 and 4–2 (the last cycle encompassing MIS 5(d)–1 inclusive). If correct, the ~40 m vertical separation between the terraces would point to an uplift rate of ~0.4 mm a^{-1}, comparable with that deduced for the Ceyhan and the Lower Orontes (see above).

The distinction between cold-climate fluvial terrace deposits and warm-climate (interglacial) raised beaches in the Latakia area provides important evidence that bears upon the long-standing debate over the climatic forcing of river-terrace formation in the Mediterranean region (see below).

4. Discussion

Thanks to the advances in understanding of Quaternary (and latest pre-Quaternary) fluvial records since the foundation of the Fluvial Archives Group (FLAG), interpretation of the sequences described here can be set in a fully international context. Of particular importance in this respect, as noted above, was the compilation of long-timescale fluvial datasets under the auspices of successive International Geoscience (IGCP) projects, IGCP 449 (Global Correlation of Late Cenozoic Fluvial Deposits: Bridgland et al., 2007a) and IGCP 528 (Fluvial sequences as evidence for landscape and climatic evolution in the Late Cenozoic: Westaway et al., 2009b). Synthesis of these data revealed patterns of sediment and aggradational terrace preservation that varied between different crustal provinces, as has been alluded to above, requiring explanation in terms of localized (regional) causal mechanisms against background global (predominantly climatic) forcing factors (cf. Bridgland and Westaway, 2008a, b; 2012, 2014).

4.1 Patterns of fluvial archive preservation represented in the study region

Of the main four preservation patterns established above, those numbered 1, 2 and 4 are represented in the study region, but there are no ultra-stable cratonic archives (pattern No. 3). Pattern 1 (classic terrace staircases) is represented by the Upper Orontes, which has apparently formed approximately one terrace per glacial–interglacial cycle, and by the systems in the rapidly uplifting region in the NE Mediterranean, the Kebir, lowermost Orontes and Ceyhan, although the accelerated uplift has prevented the preservation of extensive staircases here except in the Ceyhan through the Amanos mountains, where basalt flows have armoured the older terraces against erosion (Fig. 8). Stacked sequences (pattern 2) are found in the subsiding pull-apart basins of the Ghab in Syria and the Amik in Turkey, both within the DSFZ and drained by the Orontes (Fig. 7). The preservation patterns of fluvial archives developed in the Arabian Platform would seem to belong to Pattern 4, since they show alternations between incision and aggradation, presumably in response to alternating uplift and subsidence (Figs 4–6; 8B). This is thought to be a consequence of the

interaction between isostatic compensation by lower-crustal flow and by mantle processes (Westaway, 2012; Westaway and Bridgland, 2014). To clarify, it can be anticipated that isostatic compensation for surface processes can be generally accommodated in weak layers in the upper Earth (mantle and/or lower crust). As argued previously (Westaway, 2012; Westaway and Bridgland, 2014), it can often be difficult to distinguish between alternative locations for accommodation. Variations between different regions in the timescale of the uplift response to the effects of climatic fluctuation on surface processes points to an important role for the lower crust, since the upper mantle (asthenosphere) has long been considered to have similar properties worldwide (e.g., Peltier, 1982).

4.2 Effects of tectonic activity

As noted already, some authors have advocated tectonic activity as a driver for river terrace formation; in the Mediterranean regions this has been linked to crustal shortening in relation to the nearby convergence of the African and European plates (cf. Mather et al., 1995; Stokes and Mather, 2000, 2003; cf. Cloetingh et al., 2005, 2007). However, the widespread distribution of river terraces as ubiquitous landscape features in areas distant from plate boundaries and of known tectonic stability suggests that this mechanism can be of localized importance at best. In fact there is evidence that proximity to active tectonism has had a disruptive influence on fluvial archives in that it has led to poor preservation of clearly defined, well-separated terrace staircases. Such evidence comes from localities where the effects of Quaternary tectonic activity are overprinted onto records that can be supposed to have formed in response to regional–global drivers such as epeirogenic uplift and climatic change. The reach of the Euphrates through NE Syria provides an example, as determined by examination of the terrace record in that system between the Lake Assad reservoir, upstream of Raqqa, and Deir ez-Zor (Fig. 2). This is the reach in which the ages of the terraces are well constrained by interbedded basaltic lavas, dated using the Ar–Ar technique (Demir et al., 2007b; see above; cf. Fig. 4). Although the terraces in this reach are generally well preserved and, indeed, highly prominent landscape features, over a distance of ~40 km around and downstream of Halabiyeh (Fig. 2), they are very badly disrupted by active faulting (Abou Romieh et al., 2009; Fig. 11). As Fig. 11 shows, this disruption takes the form of short sections of terrace at anomalous heights (lower or higher than expected) and/or strongly tilted. This deformation was attributed by Abou Romieh et al. to Quaternary slip on a series of faults, some of which could be matched with faults identified in an earlier seismic survey by Litak et al. (1997). Overall there are localized zones of maximum uplift followed by minimum uplift in downstream sequence across the area of deformation, which, from structural evidence, is one of primarily right-lateral deformation, with a minor component of shortening (e.g. Litak et al., 1997; Seber et al., 2000). This deformation coincides with the northern end of the Palmyra Fold Belt (Fig. 2). From their field evidence, Abou Romieh et al. (2009) calculated an overall crustal shortening rate for the area between Masrab and the Halabiyeh Plateau ~0.1 mm a^{-1} as well as invoking the existence of a 'Syrian microplate', moving relative to the Arabian Plate to its south-east (Fig. 2). The Palmyra Fold Belt thus accommodates clockwise rotation of the Arabian Plate relative to the Syrian microplate to its north-west. This tectonic zone was previously considered to be inactive (cf. Rukieh et al., 2005) but, from the newly recognized fluvial archive data, can now be recognized as a potential cause of historic earthquakes in the Damascus–Palmyra region as well as a future seismic hazard.

Such vertical disruption occurs when there is a significant dip-slip component to fault movement. In both the Halabiyeh and Damascus areas this is due to components of reverse slip (Abou Romieh et al., 2009, 2012). In other localities discussed, such as the Middle and Lower Orontes (Fig. 7) and the Ceyhan in the Amanos Mountains (Seyrek et al., 2014), rivers have interacted with normal faults. However, in each of these cases fluvial terraces have been identified only on one side of the fault, so their tectonic disruption is less readily apparent; as already noted, some of these localities indeed mark switches from fluvial terrace development in uplifting footwalls to stacked deposition in subsiding hanging-walls (cf. Fig. 7). Nonetheless, in the aforementioned Amanos Mountains reach of the Ceyhan, fluvial terraces are preserved in the hanging-wall, indicating that this locality is uplifting; given the component of upthrow on the fault, the adjacent footwall is evidently uplifting faster, indeed uplifting so fast that no fluvial terraces have been preserved and only a gorge is evident. Conversely, in most other parts of the eastern Mediterranean region the predominant sense of active faulting has been strike-slip, notably in most of Dead Sea Fault Zone, EAFZ and NAFZ (see Fig. 2). There are many localities within these fault zones where rivers have been laterally offset by slip on such faults, the rate of this movement having been quantified from dating of the fluvial deposits or other evidence (e.g., Barka and Kadinsky-Cade, 1988; Westaway, 1994; Demir et al., 2004; Westaway et al., 2006b; Seyrek et al., 2014).

Fig. 11 hereabouts

4.3 Temperature or humidity as the key driver

The debate over whether the formation of river terraces in the Mediterranean region has been driven by glacial–interglacial temperature fluctuation, as seems clearly to be the case in NW Europe, or by fluctuations in humidity (pluvials–interpluvials) was outlined in the introduction. In the eastern Mediterranean, pluvials (periods of enhanced precipitation) can broadly be correlated with sapropels, which are organically enriched sea-floor sediment layers (e.g. Kallel et al., 2000; Casford et al., 2002, 2003). Pluvials and sapropel formation have both been broadly correlated with interglacial/interstadial periods in lower latitude areas (e.g., Deuser et al., 1976; Spaulding, 1991; Kallel et al., 2000), with glacials generally coinciding with drier episodes in the Mediterranean (cf Veldkamp et al., 2015).

One of the case studies reported here, the record from the Nahr el Kebir in NW Syria, has particular bearing on this debate. Notably, the new data from the Kebir confirm the view, previously expressed by Sanlaville (1979), that the river terrace deposits here represent the cold Pleistocene stages, just as with comparable fluvial gravels in NW Europe. Indeed, the interdigitation of cold fluvial and warm marine terraces seen in the lowermost Kebir system is similar to the relationship between comparable deposits on the south coast of England, where raised beaches formed at the northern margin of the English Channel are interwoven with river terraces in various south-coast English rivers (cf. Bridgland et al., 2004). This evidence from the Kebir is of considerable importance for the study area as a whole, given the paucity of fossils in the fluvial deposits generally and the non-occurrence of Quaternary periglaciation in lowland Mediterranean valleys; without the evidence for palaeoclimate from fossils or the direct evidence of intense cold from periglacial structures and the

cryogenic disturbance of sediments, there is little that can be brought to bear on this issue from the inland parts of the region.

5. Conclusions

Data on fluvial archives from the NE Mediterranean region reinforce previous ideas that climatic forcing has been influential in river terrace formation and that uplift and/or subsidence has had a significant influence on patterns of fluvial deposition and valley evolution, with crustal type a critical control. Some crustal blocks have been experiencing subsidence throughout the Quaternary, examples being the faulted basins along the Dead Sea Fault Zone drained by the Orontes. Sedimentary isostasy is thought to be an important positive-feedback mechanism that has sustained progressive Quaternary subsidence in these basins. Such subsiding regions represent one of four identified patterns of fluvial archive preservation. Two others are well represented in the study area. First, rivers flowing over dynamic young crust to the west of the Arabian Platform have experienced progressive uplift during the Quaternary and have formed terraces in approximate synchrony with glacial–interglacial climatic fluctuation. This applies to the Upper Orontes south of Homs in Syria and also to the Kebir in Syria and the Ceyhan and Lower Orontes in southern Turkey. However, the last three are in a region where there has been especially rapid late Quaternary uplift, so that their terraces are widely spaced and archives older than Middle Pleistocene have not survived erosion.

On the Arabian Platform the fluvial archives show a pattern implying alternating episodes of uplift and subsidence, as in the Euphrates in all studied reaches in Turkey and Syria and also in the Middle Orontes at Latamneh, or uplift and stability, as in the Tigris at Diyarbakır. Comparable patterns have been observed previously on crust that has mafic underplating at its base, constricting the overlying mobile layer to a few kilometres thickness and, thus limiting inflow of crustal material beneath uplifting areas and lessening the positive-feedback enhancement of uplift in response to erosion. Archives of this type are prevalent in crustal provinces dating from the Early or Middle Proterozoic, but are also known from younger crust with thick mafic underplating, of which the Arabian Platform is an example.

The fourth preservation pattern of fluvial archives, which is not found in the study region, occurs on cratonic crust of Archaean age and is indicative of complete absence of net uplift during the Quaternary. The nearest example to the NE Mediterranean is found in the northern Black Sea region, in the case of the River Dnieper, as described in the introduction and illustrated in Fig. 3C.

In the Latakia area of NW Syria the interrelated preservation patterns of Mediterranean marine terraces (raised beaches) and River Kebir terraces show that the latter formed during Quaternary cold stages, given that they interdigitate with the former, rather than merging with them.

The contrasting fluvial archives described here reveal the important influences of crustal properties and climatic forcing on valley evolution but do not support the view that Quaternary tectonic activity has had a significant impact on the patterns of preservation

that have been recorded. Indeed, the uplift and subsidence that has occurred has generally been isostatically driven, albeit sometimes differentially affecting fault-bounded crustal blocks in such a way as to indicate Quaternary fault movement. The effects of Quaternary tectonic activity are considered more likely to have been disruptive of these patterns, however, as in the Euphrates reach that crosses the Palmyra Fold belt, between Raqqa and Deir ez-Zor.

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Figure captions:

Figure 1 – The Mediterranean region, showing the location of fluvial systems with significant Quaternary records. The location of Figure 2, which depicts the study region in more detail, is indicated.

Figure 2 – The study area of southern Turkey and Syria, showing the location of systems described in the text in relation to crustal provinces and tectonic plate boundaries. DSFZ = Dead Sea Fault Zone; EAFZ = East Anatolian Fault Zone

Figure 3 – The Rivers of the northern Black Sea region (modified from Bridgland and Westaway, 2014; after Matoshko et al., 2002, 2004). A – Map, showing locations of transects B–D in relation to the Ukrainian Shield. B – Idealized transverse profile through the Middle–Lower Dniester terrace sediments, which are inset into Miocene fluvial basin-fill deposits; C. Transverse profile across the Middle Dnieper basin,~100 km downstream of Kiev (~240 km long); D. Transverse profile through the deposits of the Upper Don near Voronezh.

Figure 4 – Idealized transverse profile through the Euphrates terrace sequence between Raqqa and Deir ez-Zor, Syria (see Fig. 2). The stratigraphical locations of Ar–Ar dated basalts, critical for the Euphrates age model, are indicated; Euphrates deposits older than the level

of the Halabiyeh upper gravel are omitted. After Bridgland and Westaway (2014); modified from Demir et al. (2007a, b).

Figure 5 – Idealized transverse profile through the Euphrates terraces in the Birecik area, southern Turkey (see Fig. 2). Holocene flood deposits that overlie the terraces assigned to MIS 6 and 2 (cf. Kuzucuoğlu et al., 2004) are omitted. After Bridgland and Westaway (2014); modified from Demir et al. (2008).

Figure 6 – Idealized transverse profile across the River Tigris at Diyarbakır, SE Turkey (see Fig. 2), showing the disposition of terrace gravels and dated basalts. Heights were obtained by Leica dGPS with reference to Shuttle Radar Topographic Mission imagery (see Bridgland et al., 2012; Demir et al., 2012). After Bridgland and Westaway (2014); modified from Westaway et al. (2009c).

Figure 7 – Longitudinal profile of the River Orontes system, showing the distinctly different records in particular crustal zones (see text for explanation). Note the contrast between terraced reaches, gorge reaches and reaches across subsiding fluvio-lacustrine basins. Normal faults at the edges of the subsided basins are only shown where known in detail. Summaries of post-Early Pleistocene uplift histories of the terraced reaches are also shown. Modified from Bridgland et al. (2012).

Figure 8 – Comparison of the Upper and Middle terraced reaches of the River Orontes in Syria (modified from Bridgland et al., 2012). A - Idealized transverse section through the terrace sequence upstream from Homs (see Fig. 2), showing suggested ages and MIS correlations. B - Idealized transverse section through the terrace sequence of the Hama–Latamneh area (see Fig. 2), showing the thick sequence at the latter location. Suggested MIS correlations are shown. Modified from Bridgland et al. (2012), with data from Besançon and Sanlaville (1993) and Dodonov et al. (1993).

Figure 9 – Cross-section across the Ceyhan valley in the proximity of the Aslantaş Dam, near Dűziçi (Turkey), showing the relation of river terrace deposits to dated basalt lava flows. Modified from Bridgland et al. (2012), with extension to show abandoned valley section and associated terraces.

Figure 10 – Fluvial and marine terraces in the lower valley of the River Kebir, near Latakia, Syria. A – Cross section through the Kebir valley ~10 km upstream from Latakia, showing the relative disposition of the river terraces now identified, as well as the slope deposits that give rise to the (now deleted) Berzine (QIII) terrace level (see text). These same slope deposits form considerable overburden, rich in Palaeolithic artefacts, above the Jinnderiyeh terrace (Bridgland et al., 2008). B – NE–SW longitudinal profile of the Kebir terraces. After Bridgland and Westaway(2014); modified from Bridgland et al., 2008). Note the combination of deformed (interglacial) marine terraces and steeply graded colder-climate gravel terraces, which intersect with the much shallower downstream gradient of the modern (Holocene) valley floor. The deformation of the marine terraces reflects increasing uplift rates in an eastward (inland) direction.

Figure 11 – Longitudinal sections showing variations in heights of Euphrates terraces and associated basalts on the right side (a) and left side (b) of the river in the reach between Raqqa and Deir ez-Zor. Note the effects of active faulting, with increasing deformation with age of terrace. Both projections are oriented N35^{o}W–S35^{o}E with distance measured from an origin at UTM co-ordinates DV 65000 70000; the maximum deformation, at ~km 90–100, is ~10 km downstream of Halabiyeh (see Fig. 2). The French Qf (Quaternary fluvial) notation for terraces is retained, with QfI and QfII identified as distinct features. QfIII is complex; its oldest and highest division is given the temporary designation QFIIIz here, shown in purple, whereas below this are several separate fragments shown in green, various disrupted and also variously interbedded with the lava flows identified in this reach (Modified from Abou Romieh et al., 2009).

Annotated revised manuscript
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Changes in response to Reviewer 1

Changes in response to Reviewer 2

Our own edits

River terrace development in the NE Mediterranean region (Syria and Turkey): patterns in relation to crustal type

Comment [DRB1]: This amended title reflects the focus that the referees and guest editor suggest for emphasis. The word 'development' is preferred to 'preservation' as it allows for the material on the 'drivers' of terrace formation, no longer mentioned in the title.

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[Abstract]
It is widely recognized that the optimal development of river terraces globally has been in the temperate latitudes, with NW and Central Europe being areas of particular importance for the preservation of such archives of Quaternary environmental change. There is also a growing consensus that the principal drivers of terrace formation have been climatic fluctuation against a background of progressive (but variable) uplift. Nonetheless river terraces are widely preserved in the Mediterranean region, where they have often been attributed to the effects of neotectonic activity, with a continuing debate about the relative significance of fluctuating temperature (glacials–interglacials) and precipitation (pluvials–interpluvials). Research in Syria and southern–central Turkey (specifically in the valleys of the Tigris and Ceyhan in Turkey, the Kebir in Syria and the trans-border rivers Orontes and Euphrates) has underlined the importance of uplift rates in dictating the preservation pattern of fluvial archives and has revealed different patterns that can be related to crustal type. The NE Mediterranean coastal region has experienced unusually rapid uplift in the Late Quaternary. The relation between the Kebir terraces and the staircase of interglacial raised beaches preserved along the Mediterranean coastline of NW Syria reinforces previous conclusions that the emplacement of the fluvial terrace deposits in the Mediterranean has occurred during colder climatic episodes. 213 words

Keywords: River terraces; Uplift; Climatic forcing; Crustal type; Euphrates; Orontes

Highlights

Climatic fluctuation has forced river-terrace formation in the Mediterranean region

Climatic forcing has been over-printed onto the effects of background regional uplift

Differing patterns of fluvial-archive preservation reflect distinct uplift histories

Disparate uplift histories correlate with crustal type and mobility of lower crust

The effects of Quaternary tectonic activity are seen in the deformation of terraces

1. Introduction

River terraces occur in most parts of the world (Bridgland and Westaway, 2008a, b, 2014) and are common throughout the Mediterranean region (Fig. 1), being found in southern Europe (Harvey and Wells, 1987; Karner and Marra, 1998; Schoorl and Veldkamp, 2003; Stokes and Mather, 2003; Santisteban and Schulte, 2007; Meikle et al., 2010; Candy et al., 2004; Cunha et al., 2005, 2008; Zagorchev, 2007; Martins et al., 2010; Viveen et al., 2012a, b, 2013), Turkey (Demir et al., 2004; Westaway et al., 2004, 2006a; Maddy et al., 2005, 2007, 2008, 2012a), Syria (Besançon et al., 1978; Besançon and Sanlaville, 1984), Egypt (Said, 1993; Zaki, 2007; Woodward et al., 2015) and Morocco (Aït Hssaine and Bridgland, 2009; Westaway et al., 2009a). It is widely agreed that such terraces have formed in response to latest Cenozoic uplift (Van den Berg, 1994; Maddy, 1997; Antoine et al., 2000; Maddy et al., 2000, 2001; Bridgland, 2000; Van den Berg and van Hoof, 2001; Westaway, 2002a; Starkel, 2003), with an equally prevalent view that the triggering of the different fluvial activity that has led to terrace formation (essentially an alternation of down-cutting and aggradation) has been related to Quaternary climatic fluctuation, typically (but not invariably) at a glacial–interglacial frequency (for recent inter-regional reviews, see Bridgland and Westaway, 2012, 2014). While most workers have envisaged the uplift responsible for the widespread phenomenon of river terraces to be regional, epeirogenic and 'atectonic', rather than caused by plate-tectonic processes or contemporaneous fault movement (cf. Maddy et al., 2000), some have made a case for the involvement of 'active tectonics'; in the Mediterranean region these include Mather et al. (1995) and Stokes and Mather (2000, 2003), in the fault-bounded basins of southern Spain, and Boulton and Whittaker (2009) in the lowermost Orontes (Asi), Hatay Province, Turkey (see below; Fig. 2). Westaway (2002a), who has strongly advocated regional uplift as a principal control on river terrace formation, has demonstrated that the relative spacing of such terraces can be used as an indication of the strength and rapidity of the uplift. This approach has shown that uplift accelerated markedly, generally from a very low or non-existent rate, in the late Pliocene and again at the start of the Middle Pleistocene (following the Mid Pleistocene Revolution, when the 100 kyrs climatic cycles began), suggesting that the increasing severity of cold (glacial) climate cycles was an important influence, through coupling between climatic variation and Earth surface processes (Westaway, 2002a; Bridgland and Westaway, 2008a, b, 2014; Westaway et al., 2009b).

Westaway (2002a, 2006) has suggested compensation within the mobile lower continental crust as the most likely mechanism for sustaining the observed progressive regional uplift; this is envisaged as a long-term isostatic effect of the redistribution of material by erosion and sedimentation, but, unlike with glacio-isostasy, the effect is generally permanent (cf. Bridgland and Westaway, 2012, 2014). Thus lower crust has been squeezed from areas subsiding under the weight of sediment and has accumulated beneath uplifting areas, maintaining their additional elevation and providing important positive feedback in support of the isostatic effect. This mechanism cannot operate in areas where the lower crust is not mobile, as in Archaean cratons, in which the crust has cooled and solidified throughout its depth. Indeed, the observed absence of terrace sequences in such areas would seem to corroborate the envisaged mechanism, in the absence of any other explanation for such patterns of terrace occurrence (cf., Westaway et al., 2003; Bridgland and Westaway, 2008a, b, 2014; Westaway et al., 2009b). Thus the characteristic river terrace staircases observed in

Comment [DRB2]: Our own edit, but moving towards greater equivocation about the mechanism, in response to the referees.

areas such as NW Europe have formed on relatively hot, dynamic Phanerozoic crust. It has also been shown that rivers on crust of an antiquity intermediate between Archaean and Phanerozoic (i.e., Proterozoic), which generally has a limited thickness of mobile lower crust, have produced fluctuating patterns of terrace formation and accumulation, suggesting oscillations between uplift and subsidence (Westaway, 2012; Bridgland and Westaway, 2014; Westaway and Bridgland, 2014).

1.1 Patterns of fluvial archive preservation

Comment [DRB3]: New subheading fo text brought forward (suggestion from the Guest Editor, following comments from the referees).

Four main patterns of sedimentary fluvial archive preservation have been recognized thus far from the various surveys undertaken under the auspices of the Fluvial Archives Group, including successive International Geoscience (IGCP) projects: IGCP 449 (Bridgland et al., 2007a) and IGCP 518 (Westaway et al., 2009b). These preservation types are as follows: (1) typical terrace staircase archives on dynamic (Phanerozoic) crust with a mobile lower layer, (2) stacked sequences in subsiding areas, in which accumulation of sediment is a significant positive-feedback driver of the subsidence, (3) sequences in ultra-stable cratonic regions (coincident with Archaean crustal provinces), which (as noted above) show evidence for neither uplift nor subsidence, but instead for the lateral accretion of sediments of different ages (Westaway et al., 2003; Bridgland and Westaway, 2014), and (4) records intermediate between patterns 1 and 3, showing alternations of uplift and subsidence, as seen in areas with thin mobile crustal layers, often of Proterozoic age (Westaway, 2012; Bridgland and Westaway, 2014; Westaway and Bridgland, 2014; see above). The preservation patterns within archive type 1 are divisible into systems that have formed terraces in approximate synchrony with glacial–interglacial climatic fluctuation, those that have formed terraces less often than that and those (rare) systems in which terrace formation has occurred more frequently than once per glacial–interglacial cycle (Bridgland and Westaway, 2008a).

At no great distance from the NE Mediterranean is an area that has yielded a wealth of fluvial archive data, highly influential in the recognition of the above patterns: the northern Black Sea region. This area is dominated by three important southward-draining rivers: in a west–east direction, the Dniester, Dnieper and Don (Fig. 3). The records from these rivers were synthesized by Matoshko et al. (2004) and further reviewed by Bridgland and Westaway (2008a, 2014), with detail of the prevailing crustal properties and their relation to the fluvial archives was further discussed by Westaway and Bridgland (2014). All three rivers have excellent fluvial archives, benefitting from research over very many years and well constrained by biostratigraphy, loess–soils overburden sequences and geochronology (Matoshko et al., 2004). Despite their relative proximity to each other (Fig. 3A), particularly in terms of global regions and climatic zonation, the sedimentary sequences of these three rivers have markedly contrasting geometries, an observation that can be matched closely with the crustal province in which their valleys are developed. Thus the Dniester, the furthest west, and flowing over through the SW part of the Dniester–Bug crustal domain (Fig. 3A), has formed a conventional terrace staircase in a valley that has been incised into Miocene basin-fill deposits, 'basin inversion' (the start of incision) having occurred at around the beginning of the Pliocene. As Fig. 3B shows, several broad Pliocene terrace formations are preserved, as well as three classified as Lower Pleistocene, after which the river increased the steepness of its incision into the basin fill at around the Mid-Pleistocene Revolution (MPR), when the change to 100 ka interglacial–glacial climatic cycles took place

(Mudelsee et al., 1997; McCymont et al., 2008). Subsequent to this change in the pattern of climatic change, the Dniester has formed a lower staircase of terraces at approximately one per 100 kyr cycle. The overall incision pattern recorded by the Dniester is thus regarded as a response to uplift, which showed comparable changes in reaction to enhanced surface processes resulting from the climatic cooling in the late Pliocene and then again with the onset of the longer climatic cycles, with greater severity of glacials,at the MPR (Westaway, 2002a, b).

The River Dnieper, in contrast to the Dniester, flows on the cratonic crust of the Ukrainian Shield (Fig. 3A). Its sedimentary archives date back to the Miocene but show no evidence of consistent uplift since that time, there having been no progressive incision by the river. Instead the deposits occur laterally distributed over a wide area within a range of a few tens of metres above or below the modern Dnieper (Fig, 3C). This, then, provides an excellent example of the cratonic pattern of fluvial archive preservation noted above. Finally the Don, which flows over the Early Proterozoic crust of the Voronezh Shield or the Lipetsk–Losev crustal domain (Fig. 3A), has an archive of Late Cenozoic sediments that differs yet again in its preservation pattern, with evidence that the valley has experienced periods of uplift interspersed with subsidence. Thus uplift is indicated by the oldest suite of (partly buried) Don terraces, formed during the late Miocene–Pliocene (Fig. 3D). In the Early Pleistocene there were alternating shorter periods of uplift and subsidence, culminating in the aggradation of a continuous sequence representing much of the Middle Pleistocene, following which, from MIS 8 onwards, there has been further uplift and terrace formation (Fig. 3D). This, then, is an example of preservation pattern 4 (see above).

Figs 1–3 hereabouts

1.2 Consideration of other potential mechanisms for terrace generation

Comment [DRB4]: New subheading for text that we have been asked to expand upon.

The role of sea-level fluctuation as a driver for terrace formation, via its causal linkage with base-level change, has also been promoted by many workers (cf. Törnqvist and Blum, 1998; Tucker and Whipple, 2002), irrespective of crustal movements. In the Mediterranean region (albeit on the Atlantic seaboard) a convincing case has been made for glacial–interglacial eustatic change as a mechanism for terrace generation in Portugal (Martins et al., 2010; Viveen et al., 2013), where the continental shelf is narrow and sea-level change might be expected to exert a significant influence in lower fluvial reaches onshore. This mechanism has also been envisaged as a key driver for aggradation in the Tiber system, Italy (Karner and Marra, 1998), although this latter study did not consider the alternative possibility of a climatic driver. Such base-level forcing is generally envisaged to lead to progressive vertical incision by rivers from their downstream end, by the mechanism of knick-point recession (Whipple and Tucker, 1999, 2002; Roberts and White 2010; cf. Bridgland and Westaway, 2012); for a full review of this approach, and an attempt to reconcile it with evidence from river terrace sequences, see Demoulin et al., this issue).

In the warm-temperate Mediterranean climatic zone there has also been debate about whether Quaternary cycles of varying temperature (glacials–interglacials) have been important drivers of fluvial activity, as is supposed in NW Europe (e.g., Antoine et al., 2000; Bridgland, 2000), or whether humidity cycles (pluvials–interpluvials) have been more

important. Humidity fluctuations have been invoked as an important influence on rivers in the eastern Mediterranean, where they might be linked to the fluctuating strength of the Indian Ocean monsoon (e.g., Rossignol-Strick, 1985; Kroon et al., 1998), although much of the evidence is from recent timescales. Conversely Macklin et al. (2002) have compiled evidence from the last two climate cycles and found that temperature is likely to be the most important driver, as it is further north in Europe.

Working in the Gediz River system in western Turkey, which has abundant fluvial archives but has been disrupted by Late Cenozoic – Quaternary volcanism, Veldkamp et al. (2015) found evidence to support climatic forcing of river terrace formation in the Early Pleistocene. This evidence took the form of a sequence of rubified palaeosols and laminated calcretes formed at the top of fluvial (Gediz) sediments and within colluvial overburden. From micro-morphological and stable-isotope analysis they concluded that rubified soils had formed in a warm, moist and forested environment, whereas the calcretes recorded cooler and drier periods with an open (non-wooded) landscape. They inferred that the colluvial sediments represented colder periods of landscape instability, during which fluvial incision might have occurred, thus suggesting down-cutting at cooling transitions in this system. From the Ar–Ar age of a capping lava (~1.3 Ma) they suggested a tentative correlation between the formation of the various Gediz terraces and major climatic transitions during the late Early Pleistocene.

The present paper will review evidence from work carried out by the authors in Syrian and southern Turkish river systems that has a bearing of these various debates and further suggests a strong linkage between patterns of fluvial archive preservation and crustal type. The text will be organized according to crustal provinces.

Comment [DRB5]: The text above this point discusses one of the points raised by Referee 1.

Comment [DRB6]: This has been inserted at the request of Reviewer 1, in the most relevant way that can be envisaged. We would not have gone out of our way to cite this paper otherwise, which demonstrates little direct connection between the sequence in question and the Gediz terraces. Indeed, I was somewhat non-plussed by the negativity of reviewer 1's comments about our paper when I saw how poorly constrained and how vague the suggestions in his paper are!

2. Fluvial records from the northern Arabian platform

The crust of the northern Arabian Platform is of Late Proterozoic age, having consolidated during the latest Precambrian 'Pan-African' orogeny. However, it shares a characteristic with older Proterozoic crust elsewhere, in that it consists of a thick basal mafic layer overlain by a relatively thin layer of mobile felsic lower crust (cf. Demir et al., 2007a). Representing a separate tectonic plate, it is bounded to the west by the Dead Sea Fault Zone (DSFZ), which separates it from the African Plate, and to the north by the East Anatolian Fault Zone, which marks its separation from the Turkish Plate (Fig. 2). The northern Arabian Platform is drained southwards to the Persian Gulf by the twin rivers of Mesopotamia, the Tigris (Dicli) and Euphrates (Firat), while its western fringe is drained northwards by the Orontes, which follows the DSFZ for much of its course (Fig. 2).

2.1. The River Euphrates in Turkey and Syria

The fluvial record of the Euphrates has been studied by the authors in both Turkey and Syria (Demir et al., 2007a, b, 2008, 2012; Abou Romieh et al., 2009); comparison can also be made with the sequence (downstream) in Iraq, based on studies there by Tyràček (1987). This system will be considered first, as it has a more central location within the Arabian Platform. In Syria geochronological constraint on the ages of Euphrates deposits has been provided by Ar–Ar dating of basalt lavas that cap terrace gravels between Raqqa and Deir ez-Zor (Demir et al., 2007b; Fig. 4). These basalts date from 2.717 ± 0.02, 2.116 ± 0.039 and

0.402 ± 0.011 Ma and seal gravels ~65, ~45 and ~8–9 m above the modern river, respectively. Previous work by Besançon and Geyer (2003) showed that the Pleistocene sequence of the Euphrates occupies a deep infilled palaeochannel incised well below the level of the modern valley (Fig. 4). The new basalt dates allowed key stages in the formation of this valley to be calibrated, leading to a revised interpretation (Demir et al., 2007b; Bridgland and Westaway, 2014) envisaging a greater age for much of the sequence.

Fig. 4 hereabouts.

The new interpretation recognizes relative landscape stability in the Syrian reach of the Euphrates prior to ~3 Ma, followed by a phase of fluvial incision, then further relative stability before renewed incision, starting at ~2 Ma, which saw the river cut the deep palaeovalley ~30 m below its present level (Fig. 4). A 40–45 m thickness of gravel accumulated, culminating at the level of terrace QfII (using the Besançon and Geyer (2003) scheme), ~23 m above modern river level, after which renewed incision began. This 'inversion' is dated by basalt ages in combination with uplift modelling (cf. Demir et al., 2007a) to around the start of the Middle Pleistocene. It may thus mark the response of the Euphrates system to the effects on fluvial processes of the MPR, and in particular the greater intensity of glacial episodes it brought about, previously suggested as a cause of increased incision in the Dniester (see above).

Further upstream, at Birecik, southern Turkey, the same palaeovalley has been recognized, but it is disposed significantly higher within the landscape (Fig. 5), its base ~5 m above modern floodplain level (Demir et al., 2008). Its fill, the Bilgin Gravel, reaches 56 m above the modern river and has a series of terraces cut into it, presumed to date from MIS 22–12, although this is largely by analogy with the dated sequence in Syria, as there is no available geochronology from the Turkish reach of the Euphrates. This correlation is, however, supported by the occurrence of comparable Acheulian artefacts in the fill sequences of both reaches (Demir et al., 2007a, 2008). Thus the same Early–Middle Pleistocene inversion is evident north of the Syrian–Turkey border, although there has been greater uplift there in the Middle–Late Pleistocene, raising the infilled palaeovalley significantly higher in the landscape and consistent with the general southward tilt of the northern Arabian platform observed previously (Arger et al., 2000).

Fig. 5 hereabouts

In the Birecik reach an older palaeovalley-fill has been recorded, between ~100 and ~140 m above the river. This comprises the İt Dağı and Hancağız gravels, the former attributed to the Euphrates on the basis of its polymict (Anatolian) clast composition and the latter a local limestone fan deposit (Demir et al., 2008; Fig. 5). These are thought, from their disposition within the landscape (both in relation to younger Euphrates deposits and by analogy with dated deposits in the Syrian reach of the Euphrates and in the Tigris in Turkey), to date from the Early–Mid Pliocene. Studies of the Euphrates sequence ~100 km further upstream, where the river is accessible from the Şanlıurfa to Adiyaman road at Karababa bridge, have revealed the same thick sedimentary sequences attributed to prolonged aggradation phases during the Early–Mid Pliocene and during the Early Pleistocene, although the preservation and thickness of these deposits is strongly influenced by active folding thereabouts (Demir

Comment [DRB7]: Although our edit, this is added detail of reasoning in response to general referee comments.

et al., 2012). These are the Işık and Kavşut gravels, respectively. The former is associated with Pliocene coastal regression, which led to the mouth of the Euphrates migrating many hundreds of kilometres south-eastward (from north-central Syria probably as far as central Iraq), and concomitant aggradation, even though the landscape in this part of Turkey was uplifting. The Kavşut gravel is attributed to regional subsidence during the Early Pleistocene (cf. Demir et al., 2012). Once again the correlation of the thick Lower Pleistocene Kavşut Gravel at Karababa with the Bilgin Gravel at Birecik and with the equivalent palaeovalley-fill deposits in the Syrian reach of the Euphrates is supported by the recovery of Lower Palaeolithic artefacts from the first-mentioned deposits in gravel quarries in the vicinity of Karababa bridge. Note that the above interpretation includes consideration of changes in the length of the system (i.e. downstream distance to the sea, or base level), rather than an uncritical formula that simply translates elevation to age, in relation to uplift.

Comment [DRB8]: Once again, our own edit, but designed to address referee criticism.

The suggested ages of the terraces in the Turkish and Syrian reaches of the Euphrates are largely based on uplift modelling, using the technique of Westaway (2002b, 2007), with important calibration from the basalt dates in Syria (see above). Like many rivers globally, the Euphrates, in its Syrian reach, would appear to have generated terraces during only the most extreme climatic cycles, broadly equivalent to the 'supercycles' of Kukla (2005): MIS 22, 16, 12, 6, 2 (Fig. 4). A comparable sequence can be seen in Kukla's (1975, 1977) central European record from the River Svratka, Czech Republic. The reversals in the direction of vertical crustal movement evident from the Euphrates archive are comparable with those observed in the record of the Don (compare Figs 4 and 5 with Fig. 3D). Both rivers are flowing over crust with a restricted thickness of mobile layer; in the Arabian platform this has been caused by mafic underplating during the aforementioned Pan-African Orogeny.

2.2. The River Tigris in southern Turkey

The Tigris sequence has been studied in the area around and downstream of Diyarbakır (Bridgland et al., 2007b; Westaway et al, 2009c), near the northern margin of the Arabian Platform. The dating of the terrace sequence in this upper part of the Tigris has been facilitated by the interbedding of fluvial deposits with basaltic lava periodically erupted from the large Karacadağ shield volcano centred ~50 km SW of Diyarbakır. At least nine Tigris terraces have been identified (Westaway et al, 2009c; Bridgland and Westaway, 2014; Fig. 6), the highest, ~200 m above present river level, marking the switch from stacked accumulation of fluvial deposits to valley incision (basin inversion), which occurred between the mid Late Miocene and the Middle Pliocene. Widespread gravel ~60–70 m above the Tigris floodplain crops out on both sides of the valley at Diyarbakır, including beneath the basalt city walls. Dated basalts overlying this terrace have proved to represent multiple flows, implying a span of at least 150 ka during which there was no valley deepening: K–Ar/Ar–Ar dates of 1.22 ± 0.02, 1.19 ± 19 and 1.07 ± 0.03 Ma have been obtained from basalts at this level, with the distinction corroborated by different magnetic polarities in basalts on the two sides of the valley (Westaway et al, 2009c; Bridgland and Westaway, 2014; Fig. 6). It is uncertain whether the river was temporarily ponded by any of these lava flows, since no lacustrine sediments, such as have been recorded in the Gediz, in western Turkey (Maddy et al., 2012b, this issue), have been observed in the Diyarbakır reach of the Tigris.

Comment [DRB9]: Comment on possible ponding, suggested by Referee 2 added here – essentially the absence of evidence for lakes. It does, however, enable a X ref. within the special issue.

Fig. 6 hereabouts

Lower terraces record the Middle–Late Pleistocene incision by the Tigris through this basalt, forming the narrow incised valley of the modern river, perhaps responding to an acceleration (or re-commencement) of uplift following the MPR (see above). The dating of these lower terraces is further constrained by a younger dated basalt, erupted at 0.43 ± 0.02 Ma (MIS 12), capping gravel ~21–22 m above the modern river (Westaway et al, 2009c; Bridgland and Westaway, 2014; Fig. 6). The application of numerical modelling as a means of obtaining approximate ages for the terrace gravels, using the dated basalts for calibration, suggests a similar Middle Pleistocene record to that in the Euphrates, with only some glacial–interglacial climate cycles represented by terraces (these being fitted to likely isostope stages based on their relative height within the landscape: Fig. 6). The pattern of the modelled uplift history here is compatible with a thin mobile lower-crustal layer (~5–7 km thick), consistent with the known presence of the aforementioned thick layer of mafic underplating at the base of the crust beneath the Arabian Platform (Westaway, 2012; Westaway and Bridgland, 2014). In contrast with the Euphrates, and indeed with the Don (see above), the history of vertical crustal movement indicated by the Tigris sequence (Fig. 6) would appear to be a fluctuation between uplift and stability, rather than uplift and subsidence, suggesting transitional crustal properties, perhaps. The early Middle Pleistocene rate of incision, and thus of uplift, was relatively high, however: ~0.1 mm a^{-1} (Westaway et al., 2009c), with evident slowing of uplift since ~MIS 12, which is represented by a terrace relatively close to the valley floor, its age fixed from a lava date (Fig. 6).

Comment [DRB10]: Reviewer 2 asks: I would like to see more on how the modelling suggests that only some glacial-interglacial cycles are represented, and why only those are represented and others not. This is addressed by the added text (in a parentheses) a few lines lower down. We do not consider this worthy of text outside barckets.

2.3. The River Orontes in Syria

The Orontes has been studied by the authors from near the Lebanon border in western Syria to the Mediterranean SW of the Turkish city of Antakya (Bridgland et al., 2012). A notable feature of its Quaternary record is that this varies considerably between different crustal blocks, the river flowing through two subsiding pull-apart basins within the DSFZ in which stacked sedimentation has taken place throughout the Quaternary and no terraces occur (Fig. 7). There are also three gorge reaches that lack terraces, despite being located on uplifting crust, resistant rocks in these reaches having prevented the lateral migration required for terrace formation (cf. Bridgland and Westaway, 2008a, 2012; Fig. 7).

Comment [DRB11]: See comment on this by referee 1

Fig. 7 hereabouts:

On the eastern flank of the Upper Orontes, upstream of Homs, is preserved an extensive staircase of calcareously cemented Late Cenozoic terraces (Bridgland et al., 2003, 2012; Fig. 8A). Initial attempts to construct an age model for these terraces used upstream projection from a fossiliferous site in the Middle Orontes, at Latamneh, supposing that site to represent an age close to MIS 12 (based on a mixture of early Middle and late Middle Pleistocene mammalian species (Bridgland et al., 2003). Subsequent re-evaluation of the vertebrate evidence from Latamneh has suggested that it is much older; this, coupled with U-series dating of the Arjun terrace to MIS 6, led Bridgland et al. (2012) to propose the revised age model depicted in Fig. 8A. This allocates a terrace tread to every glacial–interglacial cycle following the MPR. The ages of the oldest terraces can only be approximate, but there is an upper limit provided by the 'bedrock' here, which is lacustrine

marl representing a basin filling that culminated in the early Pliocene, with inversion occurring, seemingly, before the beginning of the Pleistocene, perhaps related to the late Pliocene global cooling (see above). The lake had existed since the latest Miocene, when the Homs basalt (Ar–Ar dated ~6–4Ma: Searle et al., 2010; Westaway, 2011) was erupted into it (cf. Bridgland et al., 2012).

Fig. 8 hereabouts:

The Homs Basalt gives rise the first of the three gorge reaches along the course of the Orontes, the Rastan Gorge, separating the Upper from the Middle section of the valley (Fig. 7). In the Middle Orontes there is again a well-developed terrace record, newly discovered to extend up the eastern valley side to ~120 m above the modern river, these higher levels (marked by calcreted gravels comparable with those in the Upper Orontes) perhaps representing the Pliocene (Bridgland et al., 2012). The biostratigraphical marker at Latamneh would now be assigned an age in the region of 1.2–0.9 Ma, largely based on small-mammal faunas, interpreted in comparison with the Israeli sites at Ubeidiya and Gesher Benot Yaaqov, which are regarded as older and younger, repectively, than Latamneh (Bar-Yosef and Belmaker, 2010; Bridgland et al., 2012; cf. von Koenigswald et al., 1992; Mein and Besançon, 1993; Goren-Inbar et al., 2000). An important point of contrast with the Upper Orontes is the considerable thickness of the sediments at Latamneh: ~25 m. Given that this sequence is now attributed to the Lower Pleistocene, and that the lower-level terraces essentially appear to represent 100 kyr cycles within the late Middle and Late Pleistocene (based on the uplift modelling presented by Bridgland et al (2003), which remains valid: Fig. 8B), a comparison can be made with the sequence in the Euphrates, where thick Lower Pleistocene accumulations were inverted and incised following the MPR (Figs 4 and 5). It is possible that early Middle Pleistocene incision levels (terraces) within the vertical range of the Latamneh deposits have yet to be resolved.

Caution should applied when interpreting the evidence from Latamneh, however, since the locality lies within ~5 km of a dip-slip fault at Sheizar, which marks the eastern side of the subsiding Ghab Basin (Fig. 7) and has clearly been highly active throughout the Quaternary: its minimum Late Cenozoic vertical displacement, calculated from the depth of stacked sediments on its downstream side added to the height of the uppermost terrace deposits in the area upstream, is ~300m. A further complexity is that a tooth of the ancestral mammoth *Mammuthus meridionalis* was found at Sharia (Van Liere and Hooijer, 1961), now within the eastern outskirts of Hama, in deposits that fall within the range of altitude (relative to the valley-floor) of the Latamneh deposits. The Sharia fossil would seem to pre-date the Latamneh assemblage, which includes teeth of the more evolved mammoth *Mammuthus trogontherii* (Bridgland et al., 2012), although it could also belong within an Early Pleistocene aggradational sequence.

Thus the Middle Orontes sequence might have much in common with that in the Euphrates, representing another example of the accumulation–inversion sequence that characterizes fluvial archives from the Arabian Platform. It might be significant that in this reach the river wanders eastwards further onto the Arabian plate (and away from the DSFZ) than other parts of its course (Fig. 2), perhaps explaining why a sequence reminiscent of those on the Arabian Platform is found here. No evidence of this type of record is seen in the Upper

Comment [DRB12]: Added equivocation, as per referee suggestion

Comment [DRB13]: Reviewer 2 asks: New numerical modelling? Please present model results. Or else add an appropriate reference. **The modelling first presented by Br.et al. 2003, then reinterpreted (with no new detail shown) in 2012 stands, but with a reversal as per Arabian Platform pattern not recognized until the 2012 publication.**

Comment [DRB14]: Reviewer 2 asks: Any data on rates? How is this related to the aforementioned uplift modelling? **A description of the displacement along this fault is inserted here. It does not relate to the uplift modelling except that the terrace ages, constrained by palaeontological evidence from Latamneh, apply to both.**

Comment [DRB15]: This seemed obvious, but text now added in response to the comment from Reviewer 2

Orontes; the uppermost terraces there, attributed to the late Pliocene and Early Pleistocene (Fig. 8A), were determined from conglomerate outcrops separated by exposures of bedrock marl, indicating that discrete terrace treads are represented.

3. Fluvial records from the young, dynamic crust of the Latakia–Osmaniye area

In the area west of the DSFZ, including the coastal part of NW Syria and the Turkish regions of Hatay and the İskenderun Gulf (Fig. 2) the crustal properties reflect the typical geology of the Mediterranean region, resulting from its Cenozoic deformation in response to the subduction of the Tethys Ocean and the convergence of the African and Eurasian plates. (e.g., Aktaş and Robertson, 1984; Allen and Armstrong, 2008; Seyrek et al., 2014). Such crust, seen already in those reaches of the Orontes that flow close to the DSFZ (see above, especially the Upper Orontes), is considerably more dynamic than that of the Arabian Platform.

Comment [DRB16]: Reviewer 2: Paragraph 2 [meaning section 2?] starts with a general characterization of the Arabian platform, perhaps a similar introduction may be useful.
Added here

3.1. The Lower Orontes

Continuing the story of the Orontes, the river traverses the subsiding Ghab Basin and flows through its second gorge reach, the Darkush Gorge, cut through resistant Palaeogene limestone, which has again minimized lateral migration and prevented terrace formation (see above; Fig. 7). North of this gorge it flows into Turkey and into the second subsiding pull-apart basin, the Amik Basin (for recent discussion, see Seyrek et al., 2014), the flat surface of which forms the Antakya (Antioch) Plain (Fig. 7). Between Antakya and the Mediterranean the lowermost Orontes has contrasting terraced and gorge reaches, both indicative of uplift. Indeed, the river here flows through a coastal region, extending from Latakia (Syria) in the south to the Lower River Ceyhan in the north, near Osmaniye, that can be shown to have experienced very rapid late Quaternary uplift (Bridgland et al., 2012; Bridgland and Westaway, 2014). The Lower Orontes terraces, mapped in some detail by Erol (1963), were shown by Bridgland et al. (2012) to be formed by gravels containing mostly crystalline rocks from the Hatay ophiolite and the Precambrian–Palaeozoic succession exposed in the Amanos Mountains, to the NE. The even spacing of the five documented terraces (the lowest is too low to be shown in Fig. 7) is suggestive of regular formation in synchrony with 100 kyr climatic cycles, leading Bridgland et al. (2012) to suggest correlation with MIS 12, 10, 8, 6 and 2. Calculation of uplift rates on that basis approaches 2 mm a^{-1}, a rate far greater than in the higher parts of the Orontes valley in Syria (see above).

Comment [DRB17]: Our edit, added to accommodate referee comments

Comment [DRB18]: Reviewer 2 notes a mismatch here with the diagram' **We were aware of this at the time of submission; it has been rectified.**

The last of the three Orontes gorges, cut into resistant latest Cretaceous ophiolitic rocks, is entrenched by 400 m (Fig. 7). It ends abruptly at an escarpment that is thought to coincide with an active dip-slip fault (Tolun and Erentöz, 1962; Erol, 1963; Boulton and Whittaker, 2009; Bridgland and Westaway, 2014). Erol (1963) also documented marine terraces bordering the Mediterranean coastline and provided tentative ages for these that were used by Seyrek et al. (2008) to infer a rapid uplift rate of ~0.1–0.2 mm a^{-1} during the latest Middle Pleistocene and Late Pleistocene, in reasonable agreement with the estimate from the Lower Orontes terraces (see above).

3.2. The Lower River Ceyhan, in the area of Osmaniye, southern Turkey

If the rapidity of uplift in the Lower Orontes requires estimation and inference, that indicated by the sequence in the River Ceyhan, ~50 km to the north, is well constrained by Quaternary basaltic lava that overlies fluvial levels down to the 4th terrace (of seven), ~90 m above floodplain level, which has an Ar–Ar age of 278 ± 7 ka, placing its eruption within MIS 9 (Seyrek at al., 2008). The three lower terraces, well spaced in terms of relative height, are thus attributable to MIS 8, 6 and 2 (Fig. 9). These data have provided an uplift rate for the late Middle and Late Pleistocene of 0.25–0.4 mm a^{-1}, increasing upstream (based on heights above the valley floor of well-dated terraces), perhaps in association with movement of the active fault that has uplifted the Amanos Mountains in this part of the northern DSFZ (Seyrek at al., 2008). This work has also elucidated the sequence of earlier terraces, partly preserved within an abandoned reach from which the river was probably diverted as a result of the basalt eruption (Fig. 9). Further upstream, the Ceyhan has cut a substantial gorge, up to ~2000 m deep, through the northern Amanos Mountains, the maximum age for the initiation of incision being the start of the fault movement, ~3.7 Ma (Westaway et al., 2006b), implying an average rate of down-cutting of ~0.54 mm a^{-1}, higher than the range calculated from the lower-level river terraces (see above). As Seyrek et al (2014) have established, this gorge reach of the Ceyhan is in the footwall (upthrown side) of an active normal fault, whereas the terraced reach further downstream is in its hanging (downthrown) wall, all of which is entirely consistent with the aforementioned differential uplift rates.

Fig. 9 hereabouts

3.3. The Nahr el Kebir, NW Syria

The third river draining through this zone of rapid-uplift is the Nahr el Kebir, which debouches into the Mediterranean at Latakia, its terraces interwoven with a sequence of upper Middle–Upper Pleistocene raised beaches (Copeland and Hours, 1978; Sanlaville, 1979; Devyatkin et al., 1996; Bridgland et al., 2008; Bridgland and Westaway, 2014). Considerable research has been undertaken on the Kebir terraces, largely because of their association with Palaeolithic artefacts (e.g., Copeland and Hours, 1979; Hours, 1981, 1994; Besançon et al., 1988). In summary of much work in the late 20th Century, Sanlaville (1979) attributed the fluvial terraces of the Kebir to Pleistocene cold stages (glacials) and the coastal marine terraces to interglacials. Recent work by the authors (Bridgland et al., 2008; Fig. 10) has found that the Sanlaville terrace scheme in the Kebir valley requires revision but has upheld their interpretation as cold-stage deposits, which interdigitate, rather than coalesce, with the raised marine terraces (Fig. 9A). The latter can also be confirmed as raised beaches from their bedding characteristics and patchily preserved molluscan fossils (cf. Devyatkin et al., 1996). These observations provide important corroboration of the view, from Macklin et al. (2002) amongst others, that river terrace formation in the Mediterranean region has been driven by cyclic temperature fluctuation rather than humidity cycles, although it is uncertain whether this is via a direct influence on fluvial activity and slope stability, as envisaged for systems in NW Europe (cf. Maddy, 1997; Bridgland 2000), or through the eustatic control of base level, as posited for Portuguese rivers (see above).

Fig. 10 hereabouts

Comment [DRB19]: Reviewer 2 asks how the data show un upstream increase in uplift rates. **Text added for explanation**

Comment [DRB20]: Reviewer 2 asks: I would not compare a 3.7 Ma averaged incision rate with a 300ka averaged incision rate. In general because of known variations in climate driven incision rates (as stated in your introduction and your earlier work), and in particular for this example because of the aforementioned basalt-induced drainage diversion and fault activity. This would potentially have affected incision rates significantly on the 300ka timescale. Therefore either remove or explain comparison.
This is not intended as a major contrast, it is mere relating empirical evidence based on ages that can be calculated for the of the features concerned. We have added extra text on the relation of the Ceyhan Gorge to active faulting to further differentiate the two reported sets of features.

Comment [DRB21]: Our edit, but this is additional discussion added in response to Reviewer 1.

Whereas the Sanlaville (1979) terrace scheme envisaged four terraces diverging downstream, the revised interpretation (depicted in Fig. 10B) shows four broadly parallel terraces, all significantly steeper than the modern floodplain. One of the Sanlaville terraces has been deleted from the scheme, since it can be shown to consist only of erosional remnants of slope deposits (Fig. 10A), but an additional formation has been identified just above the modern floodplain, from exposures in recent quarry workings. Bridgland et al. (2008) suggested that the four recorded terraces were formed in synchrony with the last four 100 kyr (glacial–interglacial) climate cycles, thus representing MIS 10, 8, 6 and 4–2 (the last cycle encompassing MIS 5(d)–1 inclusive). If correct, the ~40 m vertical separation between the terraces would point to an uplift rate of ~0.4 mm a^{-1}, comparable with that deduced for the Ceyhan and the Lower Orontes (see above).

The distinction between cold-climate fluvial terrace deposits and warm-climate (interglacial) raised beaches in the Latakia area provides important evidence that bears upon the long-standing debate over the climatic forcing of river-terrace formation in the Mediterranean region (see below).

4. Discussion

Thanks to the advances in understanding of Quaternary (and latest pre-Quaternary) fluvial records since the foundation of the Fluvial Archives Group (FLAG), interpretation of the sequences described here can be set in a fully international context. Of particular importance in this respect, as noted above, was the compilation of long-timescale fluvial datasets under the auspices of successive International Geoscience (IGCP) projects, IGCP 449 (Global Correlation of Late Cenozoic Fluvial Deposits: Bridgland et al., 2007a) and IGCP 528 (Fluvial sequences as evidence for landscape and climatic evolution in the Late Cenozoic: Westaway et al., 2009b). Synthesis of these data revealed patterns of sediment and aggradational terrace preservation that varied between different crustal provinces, as has been alluded to above, requiring explanation in terms of localized (regional) causal mechanisms against background global (predominantly climatic) forcing factors (cf. Bridgland and Westaway, 2008a, b; 2012, 2014). The conclusions reached form an alternative, incompatible explanation of river-system evolution to that promoted by other approaches, such as the application of 'stream power law' (Rosenbloom and Anderson, 1994; Whipple and Tucker, 1999, 2002; Snyder et al., 2000; Kirby and Whipple, 2001; Crosby and Whipple, 2006; Roberts and White 2010). This latter method seeks to model drainage evolution on the basis of the occurrence of knickpoints in river longitudinal profiles, interpreting such knickpoints (short steep reaches) as representing past falls in base level, manifested at the river mouth but having subsequently migrated upstream. A number of important assumptions are made, all of which are open to criticism: (1) discharge increases systematically downstream (not necessarily the case for large systems traversing different climatic zones; clearly invalid for the endoreic systems that die out in the deserts of North Africa or Australia); (2) all reaches of a given river have experienced the same uplift history (patently untrue in many systems, including those reported in this present paper); (3) modern discharge can be used as a basis for analysis irrespective of the effects of past climate change (whereas in fact the latter will have served to extend and shorten rivers in conjunction with sea-level fluctuation, in synchrony with glacial–interglacial climatic

oscillation, albeit that this is not regarded as a significance influence on fluvial systems other than in coastal regions, as noted above). In connection with assumption No. 2, rivers such as the Orontes, switching between uplifting and subsiding reaches, are by no means uncommon, and include the two largest rivers of Europe, the Rhine (Brunnacker et al., 1982; Ruegg, 1994; Meyer and Stets, 2002; Westaway and Bridgland, 2010) and the Danube (Gábris and Nádor, 2007; Miklós and Neppel, 2010).

4.1 Patterns of fluvial archive preservation represented in the study region

Of the main four preservation patterns established above, those numbered 1, 2 and 4 are represented in the study region, but there are no ultra-stable cratonic archives (pattern No. 3). Pattern 1 (classic terrace staircases) is represented by the Upper Orontes, which has apparently formed approximately one terrace per glacial–interglacial cycle, and by the systems in the rapidly uplifting region in the NE Mediterranean, the Kebir, lowermost Orontes and Ceyhan, although the accelerated uplift has prevented the preservation of extensive staircases here except in the Ceyhan through the Amanos mountains, where basalt flows have armoured the older terraces against erosion (Fig. 8). Stacked sequences (pattern 2) are found in the subsiding pull-apart basins of the Ghab in Syria and the Amik in Turkey, both within the DSFZ and drained by the Orontes (Fig. 7). The preservation patterns of fluvial archives developed in the Arabian Platform would seem to belong to Pattern 4, since they show alternations between incision and aggradation, presumably in response to alternating uplift and subsidence (Figs 4–6; 8B). This is thought to be a consequence of the interaction between isostatic compensation by lower-crustal flow and by mantle processes (Westaway, 2012; Westaway and Bridgland, 2014). To clarify, it can be anticipated that isostatic compensation for surface processes can be generally accommodated in weak layers in the upper Earth (mantle and/or lower crust). As argued previously (Westaway, 2012; Westaway and Bridgland, 2014), it can often be difficult to distinguish between alternative locations for accommodation. Variations between different regions in the timescale of the uplift response to the effects of climatic fluctuation on surface processes points to an important role for the lower crust, since the upper mantle (asthenosphere) has long been considered to have similar properties worldwide (e.g., Peltier, 1982).

4.2 Effects of tectonic activity

As noted already, some authors have advocated tectonic activity as a driver for river terrace formation; in the Mediterranean regions this has been linked to crustal shortening in relation to the nearby convergence of the African and European plates (cf. Mather et al., 1995; Stokes and Mather, 2000, 2003; cf. Cloetingh et al., 2005, 2007). However, the widespread distribution of river terraces as ubiquitous landscape features in areas distant from plate boundaries and of known tectonic stability suggests that this mechanism can be of localized importance at best. In fact there is evidence that proximity to active tectonism has had a disruptive influence on fluvial archives in that it has led to poor preservation of clearly defined, well-separated terrace staircases. Such evidence comes from localities where the effects of Quaternary tectonic activity are overprinted onto records that can be supposed to have formed in response to regional–global drivers such as epeirogenic uplift and climatic change. The reach of the Euphrates through NE Syria provides an example, as determined by examination of the terrace record in that system between the Lake Assad reservoir, upstream of Raqqa, and Deir ez-Zor (Fig. 2). This is the reach in which the ages of

Comment [DRB22]: Reviewer 2 asks: Could you clarify how exactly the conclusions form an incompatible explanation as opposed to the stream power law? The list of limitations or boundary conditions for using the stream power law do not clarify this statement enough. Publications such as Lague et al., (2014) discuss some of the limitations of the stream power law. But apart from that, I feel that you are not comparing like with like. Furthermore, these are two different approaches which have not met but may do so at some point:

The fluvial evolution described in this paper is based on field evidence, dating if present, and the main assumption of climate-driven terrace formation in every case, which then subsequently can be used to model uplift rates. Except for identifying the relation between driving mechanisms and river incision, there is no explanation in this paper at all on how the river does it.

Reconstructions using the stream power law are an attempt to do this, as it models fluvial evolution over time, thus understanding the pathway through time of the fluvial profile. This is often done under certain boundary conditions, some of which are mentioned in this highlighted text.

However for structurally complex rivers these boundary conditions may of course not apply, or change along the river profile.

Dismissing the stream power law based on the identified correlations between river terraces and crustal blocks in this highlighted text and in the rest of the paper comes across rather pointless to me, as no actual alternative process-driven pathway of the river incision itself is proposed.

This section has been deleted

Comment [DRB23]: Reviewer 2: This paragraph states a clear example of how tectonics can disrupt clear preservation of terrace staircase. But do the authors mean to conclude anything general about the effects of tectonics on terrace staircase formation in the region? More rivers discussed in this paper cross active faults. Do they all cause disturbed terrace preservation?

the terraces are well constrained by interbedded basaltic lavas, dated using the Ar–Ar technique (Demir et al., 2007b; see above; cf. Fig. 4). Although the terraces in this reach are generally well preserved and, indeed, highly prominent landscape features, over a distance of ~40 km around and downstream of Halabiyeh (Fig. 2), they are very badly disrupted by active faulting (Abou Romieh et al., 2009; Fig. 11). As Fig. 11 shows, this disruption takes the form of short sections of terrace at anomalous heights (lower or higher than expected) and/or strongly tilted. This deformation was attributed by Abou Romieh et al. to Quaternary slip on a series of faults, some of which could be matched with faults identified in an earlier seismic survey by Litak et al. (1997). Overall there are localized zones of maximum uplift followed by minimum uplift in downstream sequence across the area of deformation, which, from structural evidence, is one of primarily right-lateral deformation, with a minor component of shortening (e.g. Litak et al., 1997; Seber et al., 2000). This deformation coincides with the northern end of the Palmyra Fold Belt (Fig. 2). From their field evidence, Abou Romieh et al. (2009) calculated an overall crustal shortening rate for the area between Masrab and the Halabiyeh Plateau ~0.1 mm a^{-1} as well as invoking the existence of a 'Syrian microplate', moving relative to the Arabian Plate to its south-east (Fig. 2). The Palmyra Fold Belt thus accommodates clockwise rotation of the Arabian Plate relative to the Syrian microplate to its north-west. This tectonic zone was previously considered to be inactive (cf. Rukieh et al., 2005) but, from the newly recognized fluvial archive data, can now be recognized as a potential cause of historic earthquakes in the Damascus–Palmyra region as well as a future seismic hazard.

Such vertical disruption occurs when there is a significant dip-slip component to fault movement. In both the Halabiyeh and Damascus areas this is due to components of reverse slip (Abou Romieh et al., 2009, 2012). In other localities discussed, such as the Middle and Lower Orontes (Fig. 7) and the Ceyhan in the Amanos Mountains (Seyrek et al., 2014), rivers have interacted with normal faults. However, in each of these cases fluvial terraces have been identified only on one side of the fault, so their tectonic disruption is less readily apparent; as already noted, some of these localities indeed mark switches from fluvial terrace development in uplifting footwalls to stacked deposition in subsiding hanging-walls (cf. Fig. 7). Nonetheless, in the aforementioned Amanos Mountains reach of the Ceyhan, fluvial terraces are preserved in the hanging-wall, indicating that this locality is uplifting; given the component of upthrow on the fault, the adjacent footwall is evidently uplifting faster, indeed uplifting so fast that no fluvial terraces have been preserved and only a gorge is evident. Conversely, in most other parts of the eastern Mediterranean region the predominant sense of active faulting has been strike-slip, notably in most of Dead Sea Fault Zone, EAFZ and NAFZ (see Fig. 2). There are many localities within these fault zones where rivers have been laterally offset by slip on such faults, the rate of this movement having been quantified from dating of the fluvial deposits or other evidence (e.g., Barka and Kadinsky-Cade, 1988; Westaway, 1994; Demir et al., 2004; Westaway et al., 2006b; Seyrek et al., 2014).

Comment [DRB24]: This latter point was emphasized in the comments of Reviewer 1.

Fig. 11 hereabouts

4.3 Temperature or humidity as the key driver

The debate over whether the formation of river terraces in the Mediterranean region has been driven by glacial–interglacial temperature fluctuation, as seems clearly to be the case in NW Europe, or by fluctuations in humidity (pluvials–interpluvials) was outlined in the introduction. In the eastern Mediterranean, pluvials (periods of enhanced precipitation) can broadly be correlated with sapropels, which are organically enriched sea-floor sediment layers (e.g. Kallel et al., 2000; Casford et al., 2002, 2003). Pluvials and sapropel formation have both been broadly correlated with interglacial/interstadial periods in lower latitude areas (e.g., Deuser et al., 1976; Spaulding, 1991; Kallel et al., 2000), with glacials generally coinciding with drier episodes in the Mediterranean (cf Veldkamp et al., 2015).

One of the case studies reported here, the record from the Nahr el Kebir in NW Syria, has particular bearing on this debate. Notably, the new data from the Kebir confirm the view, previously expressed by Sanlaville (1979), that the river terrace deposits here represent the cold Pleistocene stages, just as with comparable fluvial gravels in NW Europe. Indeed, the interdigitation of cold fluvial and warm marine terraces seen in the lowermost Kebir system is similar to the relationship between comparable deposits on the south coast of England, where raised beaches formed at the northern margin of the English Channel are interwoven with river terraces in various south-coast English rivers (cf. Bridgland et al., 2004). This evidence from the Kebir is of considerable importance for the study area as a whole, given the paucity of fossils in the fluvial deposits generally and the non-occurrence of Quaternary periglaciation in lowland Mediterranean valleys; without the evidence for palaeoclimate from fossils or the direct evidence of intense cold from periglacial structures and the cryogenic disturbance of sediments, there is little that can be brought to bear on this issue from the inland parts of the region.

Comment [DRB25]: Discussion of this paper has already appeared above

Comment [DRB26]: The above section has been beefed up in response to Reviewer 1, although there was already a discussion section devoted to this issue.

Comment [DRB27]: Referee 2 suggests: I would suggest to structure the conclusions a bit more. Mainly along the observed 4 patterns. This has been done as part of the edit.

5. Conclusions

Data on fluvial archives from the NE Mediterranean region reinforce previous ideas that climatic forcing has been influential in river terrace formation and that uplift and/or subsidence has had a significant influence on patterns of fluvial deposition and valley evolution, with crustal type a critical control. Some crustal blocks have been experiencing subsidence throughout the Quaternary, examples being the faulted basins along the Dead Sea Fault Zone drained by the Orontes. Sedimentary isostasy is thought to be an important positive-feedback mechanism that has sustained progressive Quaternary subsidence in these basins. Such subsiding regions represent one of four identified patterns of fluvial archive preservation. Two others are well represented in the study area. First, rivers flowing over dynamic young crust to the west of the Arabian Platform have experienced progressive uplift during the Quaternary and have formed terraces in approximate synchrony with glacial–interglacial climatic fluctuation. This applies to the Upper Orontes south of Homs in Syria and also to the Kebir in Syria and the Ceyhan and Lower Orontes in southern Turkey. However, the last three are in a region where there has been especially rapid late Quaternary uplift, so that their terraces are widely spaced and archives older than Middle Pleistocene have not survived erosion.

On the Arabian Platform the fluvial archives show a pattern implying alternating episodes of uplift and subsidence, as in the Euphrates in all studied reaches in Turkey and Syria and also

in the Middle Orontes at Latamneh, or uplift and stability, as in the Tigris at Diyarbakır. Comparable patterns have been observed previously on crust that has mafic underplating at its base, constricting the overlying mobile layer to a few kilometres thickness and, thus limiting inflow of crustal material beneath uplifting areas and lessening the positive-feedback enhancement of uplift in response to erosion. Archives of this type are prevalent in crustal provinces dating from the Early or Middle Proterozoic, but are also known from younger crust with thick mafic underplating, of which the Arabian Platform is an example.

The fourth preservation pattern of fluvial archives, which is not found in the study region, occurs on cratonic crust of Archaean age and is indicative of complete absence of net uplift during the Quaternary. The nearest example to the NE Mediterranean is found in the northern Black Sea region, in the case of the River Dnieper, as described in the introduction and illustrated in Fig. 3C.

In the Latakia area of NW Syria the interrelated preservation patterns of Mediterranean marine terraces (raised beaches) and River Kebir terraces show that the latter formed during Quaternary cold stages, given that they interdigitate with the former, rather than merging with them.

The contrasting fluvial archives described here reveal the important influences of crustal properties and climatic forcing on valley evolution but do not support the view that Quaternary tectonic activity has had a significant impact on the patterns of preservation that have been recorded. Indeed, the uplift and subsidence that has occurred has generally been isostatically driven, albeit sometimes differentially affecting fault-bounded crustal blocks in such a way as to indicate Quaternary fault movement. The effects of Quaternary tectonic activity are considered more likely to have been disruptive of these patterns, however, as in the Euphrates reach that crosses the Palmyra Fold belt, between Raqqa and Deir ez-Zor.

Comment [DRB28]: Reviewer 2: I would like to see the argumentation supporting this conclusion better conveyed in the main text. See comments on section 4.2

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Figure captions:

Figure 1 – The Mediterranean region, showing the location of fluvial systems with significant Quaternary records. The location of Figure 2, which depicts the study region in more detail, is indicated.

Figure 2 – The study area of southern Turkey and Syria, showing the location of systems described in the text in relation to crustal provinces and tectonic plate boundaries. DSFZ = Dead Sea Fault Zone; EAFZ = East Anatolian Fault Zone

Figure 3 – The Rivers of the northern Black Sea region (modified from Bridgland and Westaway, 2014; after Matoshko et al., 2002, 2004). A – Map, showing locations of transects B–D in relation to the Ukrainian Shield. B – Idealized transverse profile through the Middle–Lower Dniester terrace sediments, which are inset into Miocene fluvial basin-fill deposits; C. Transverse profile across the Middle Dnieper basin,~100 km downstream of Kiev (~240 km long); D. Transverse profile through the deposits of the Upper Don near Voronezh.

Figure 4 – Idealized transverse profile through the Euphrates terrace sequence between Raqqa and Deir ez-Zor, Syria (see Fig. 2). The stratigraphical locations of Ar–Ar dated basalts, critical for the Euphrates age model, are indicated; Euphrates deposits older than the level of the Halabiyeh upper gravel are omitted. After Bridgland and Westaway (2014); modified from Demir et al. (2007a, b).

Figure 5 – Idealized transverse profile through the Euphrates terraces in the Birecik area, southern Turkey (see Fig. 2). Holocene flood deposits that overlie the terraces assigned to MIS 6 and 2 (cf. Kuzucuoğlu et al., 2004) are omitted. After Bridgland and Westaway (2014); modified from Demir et al. (2008).

Figure 6 – Idealized transverse profile across the River Tigris at Diyarbakır, SE Turkey (see Fig. 2), showing the disposition of terrace gravels and dated basalts. Heights were obtained by Leica dGPS with reference to Shuttle Radar Topographic Mission imagery (see Bridgland et al., 2012; Demir et al., 2012). After Bridgland and Westaway (2014); modified from Westaway et al. (2009c).

Figure 7 – Longitudinal profile of the River Orontes system, showing the distinctly different records in particular crustal zones (see text for explanation). Note the contrast between terraced reaches, gorge reaches and reaches across subsiding fluvio-lacustrine basins. Normal faults at the edges of the subsided basins are only shown where known in detail. Summaries of post-Early Pleistocene uplift histories of the terraced reaches are also shown. Modified from Bridgland et al. (2012).

Figure 8 – Comparison of the Upper and Middle terraced reaches of the River Orontes in Syria (modified from Bridgland et al., 2012). A - Idealized transverse section through the terrace sequence upstream from Homs (see Fig. 2), showing suggested ages and MIS correlations. B - Idealized transverse section through the terrace sequence of the Hama–Latamneh area (see Fig. 2), showing the thick sequence at the latter location. Suggested MIS correlations are shown. Modified from Bridgland et al. (2012), with data from Besançon and Sanlaville (1993) and Dodonov et al. (1993).

Figure 9 – Cross-section across the Ceyhan valley in the proximity of the Aslantaş Dam, near Dűziçi (Turkey), showing the relation of river terrace deposits to dated basalt lava flows. Modified from Bridgland et al. (2012), with extension to show abandoned valley section and associated terraces.

Figure 10 – Fluvial and marine terraces in the lower valley of the River Kebir, near Latakia, Syria. A – Cross section through the Kebir valley ~10 km upstream from Latakia, showing the relative disposition of the river terraces now identified, as well as the slope deposits that give rise to the (now deleted) Berzine (QIII) terrace level (see text). These same slope deposits form considerable overburden, rich in Palaeolithic artefacts, above the Jinnderiyeh terrace (Bridgland et al., 2008). B – NE–SW longitudinal profile of the Kebir terraces. After Bridgland and Westaway(2014); modified from Bridgland et al., 2008). Note the combination of deformed (interglacial) marine terraces and steeply graded colder-climate gravel terraces, which intersect with the much shallower downstream gradient of the modern (Holocene) valley floor. The deformation of the marine terraces reflects increasing uplift rates in an eastward (inland) direction. **[This diagram has been reorganized]**

Figure 11 – Longitudinal sections showing variations in heights of Euphrates terraces and associated basalts on the right side (a) and left side (b) of the river in the reach between Raqqa and Deir ez-Zor. Note the effects of active faulting, with increasing deformation with age of terrace. Both projections are oriented N35^{o}W–S35^{o}E with distance measured from an origin at UTM co-ordinates DV 65000 70000; the maximum deformation, at ~km 90–100, is ~10 km downstream of Halabiyeh (see Fig. 2). The French Qf (Quaternary fluvial) notation for terraces is retained, with QfI and QfII identified as distinct features. QfIII is complex; its oldest and highest division is given the temporary designation QFIIIz here, shown in purple, whereas below this are several separate fragments shown in green, various disrupted and also variously interbedded with the lava flows identified in this reach (Modified from Abou Romieh et al., 2009).

Figure 1

FIGURE 3A
FIGURE 2
Don
Dniester
Dnieper
Danube
Po
Rhône
Tiber
Struma
Mesta
Gediz
Büyük Menderes
Göksu
Dalaman
Aksu
Miño
Duero
Ebro
Tagus
Guadiana
Guadalquivir
Aguas
Guadalhorce
Souss
Ifni
Nile

Figure 2

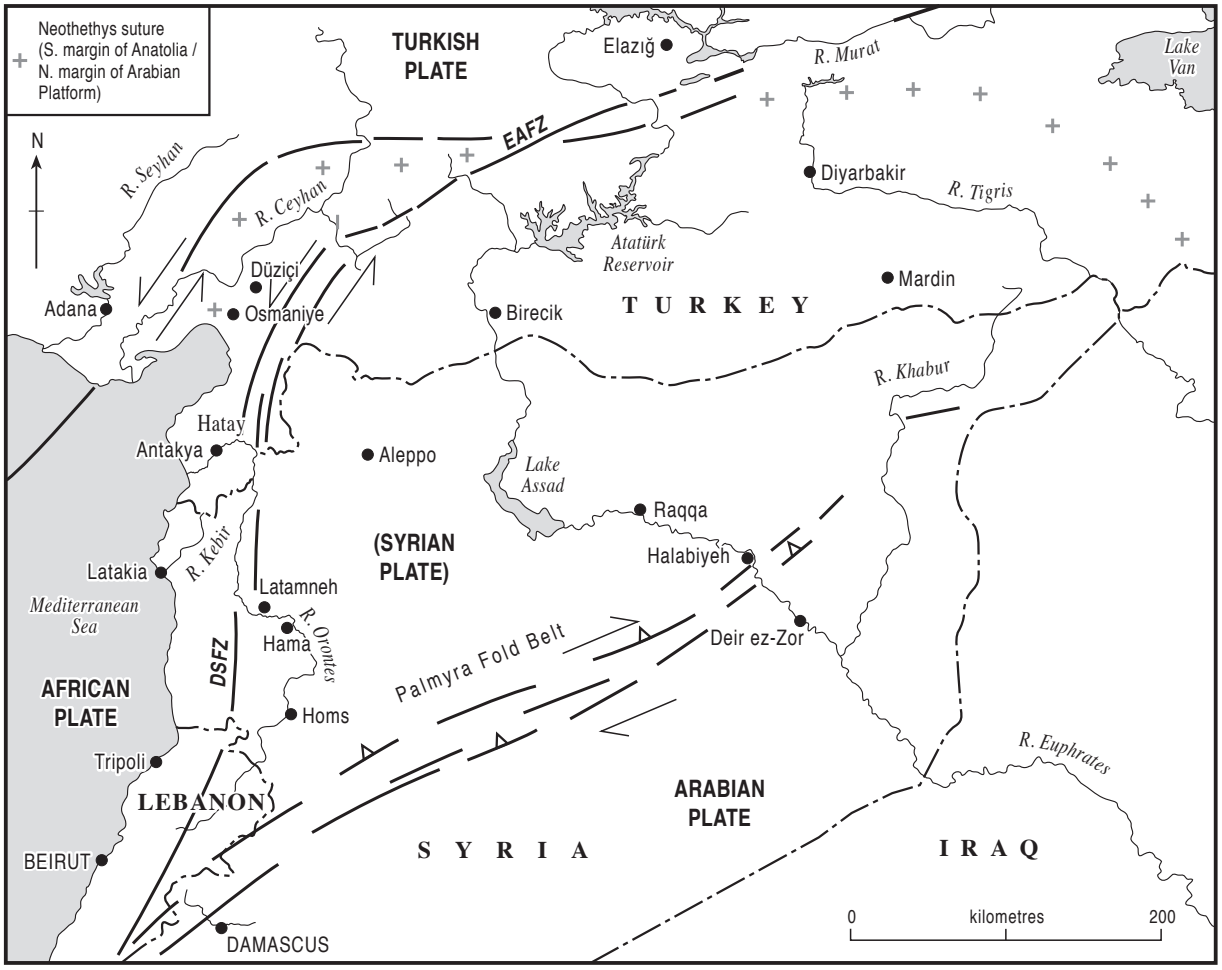

Neothethys suture
(S. margin of Anatolia /
N. margin of Arabian
Platform)
N
TURKISH
PLATE
Elazığ
R. Murat
Lake
Van
EAFZ
R. Seyhan
R. Ceyhan
Diyarbakir
R. Tigris
Atatürk
Reservoir
Düziçi
Adana
Osmaniye
Birecik
T U R K E Y
Mardin
R. Khabur
Hatay
Antakya
Aleppo
Lake
Assad
Raqqa
(SYRIAN
PLATE)
Halabiyeh
Latakia
R. Kebir
Latamneh
Mediterranean
Sea
R. Orontes
Hama
DSFZ
Palmyra Fold Belt
Deir ez-Zor
AFRICAN
PLATE
Homs
R. Euphrates
Tripoli
LEBANON
ARABIAN
PLATE
BEIRUT
S Y R I A
I R A Q
DAMASCUS
0
kilometres
200

Figure 3

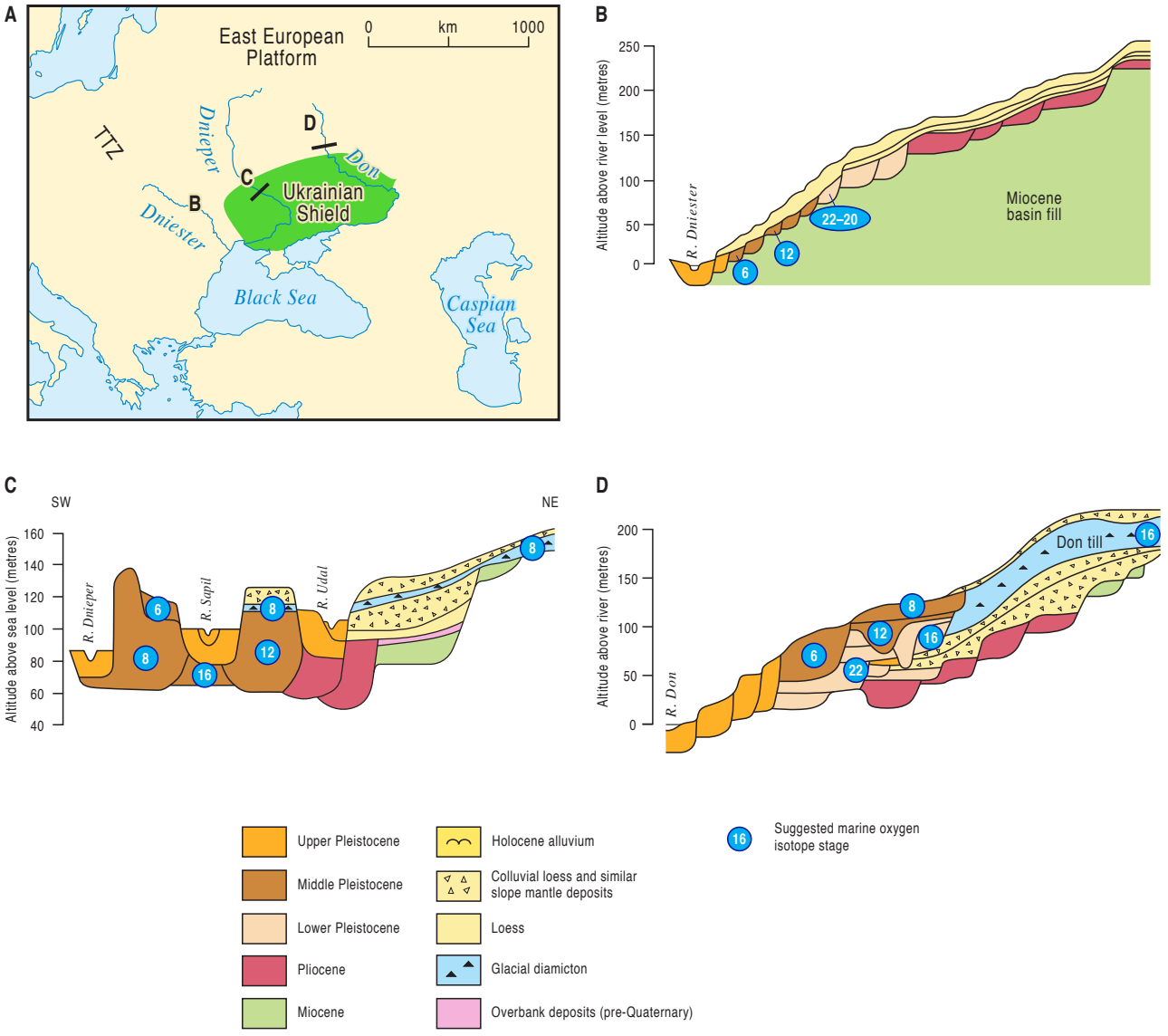

A
East European Platform
0 km 1000
TTZ
Dnieper
Dniester
Don
Ukrainian Shield
Black Sea
Caspian Sea
B
C
D
B
Altitude above river level (metres)
250
200
150
100
50
0
R. Dniester
Miocene basin fill
22–20
12
6
C
SW
NE
Altitude above sea level (metres)
160
140
120
100
80
60
40
R. Dnieper
R. Sapil
R. Udal
6
8
16
8
12
8
D
Altitude above river (metres)
200
150
100
50
0
R. Don
Don till
16
8
12
16
6
22
Upper Pleistocene
Middle Pleistocene
Lower Pleistocene
Pliocene
Miocene
Holocene alluvium
Colluvial loess and similar slope mantle deposits
Loess
Glacial diamicton
Overbank deposits (pre-Quaternary)
16
Suggested marine oxygen isotope stage

Figure 4

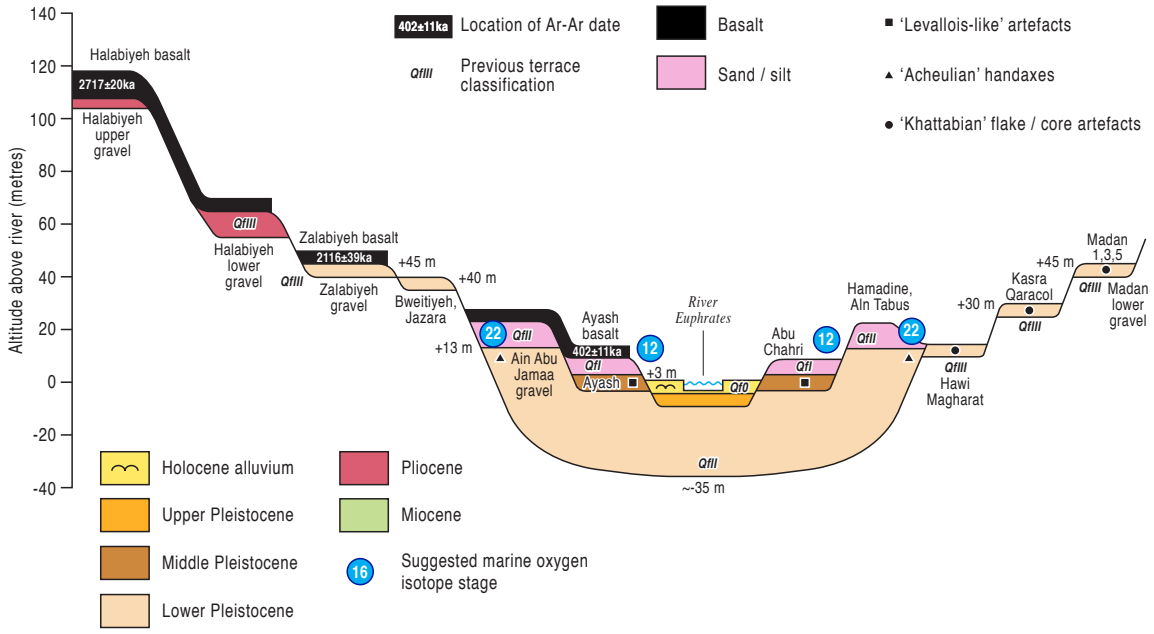

Altitude above river (metres)
140
120
100
80
60
40
20
0
-20
-40
402±11ka Location of Ar-Ar date
Qfiii Previous terrace classification
Basalt
Sand / silt
'Levallois-like' artefacts
'Acheulian' handaxes
'Khattabian' flake / core artefacts
Halabiyeh basalt
2717±20ka
Halabiyeh upper gravel
Qfiii
Halabiyeh lower gravel
Qfiii
Zalabiyeh basalt
2116±39ka
Zalabiyeh gravel
+45 m
+40 m
Bweitiyeh, Jazara
+13 m
22
Qfii
Ain Abu Jamaa gravel
Ayash basalt
402±11ka
Qfi
Ayash
12
+3 m
River Euphrates
Qfi0
Abu Chahri
12
Qfi
Hamadine, Aln Tabus
Qfii
22
+30 m
Qfiii
Hawi Magharat
Kasra Qaracol
Qfiii
+45 m
Madan 1,3,5
Qfiii
Madan lower gravel
Qfii
~-35 m
Holocene alluvium
Upper Pleistocene
Middle Pleistocene
Lower Pleistocene
Pliocene
Miocene
16
Suggested marine oxygen isotope stage

Figure 5

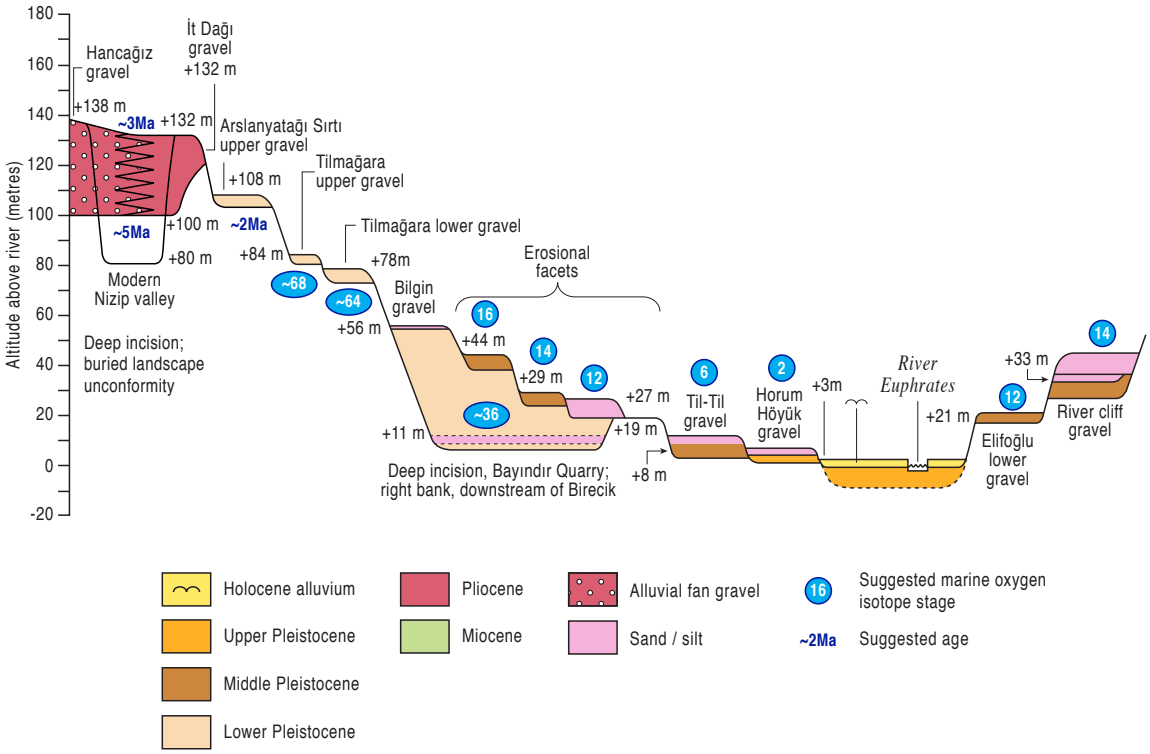

Altitude above river (metres)
180
160
140
120
100
80
60
40
20
0
-20
Hancağız gravel
+138 m
~3Ma
İt Dağı gravel +132 m
+132 m
Arslanyatağı Sırtı upper gravel
+108 m
Tilmağara upper gravel
~5Ma
+100 m
~2Ma
+84 m
Tilmağara lower gravel
+78m
+80 m
Modern Nizip valley
~68
~64
+56 m
Bilgin gravel
Erosional facets
16
+44 m
14
+29 m
12
+27 m
Deep incision; buried landscape unconformity
~36
+11 m
+19 m
+8 m
Deep incision, Bayındır Quarry; right bank, downstream of Birecik
6
Til-Til gravel
2
Horum Höyük gravel
+3m
River Euphrates
+21 m
12
Elifoğlu lower gravel
+33 m
14
River cliff gravel
Holocene alluvium
Upper Pleistocene
Middle Pleistocene
Lower Pleistocene
Pliocene
Miocene
Alluvial fan gravel
Sand / silt
16
Suggested marine oxygen isotope stage
~2Ma
Suggested age

Figure 6

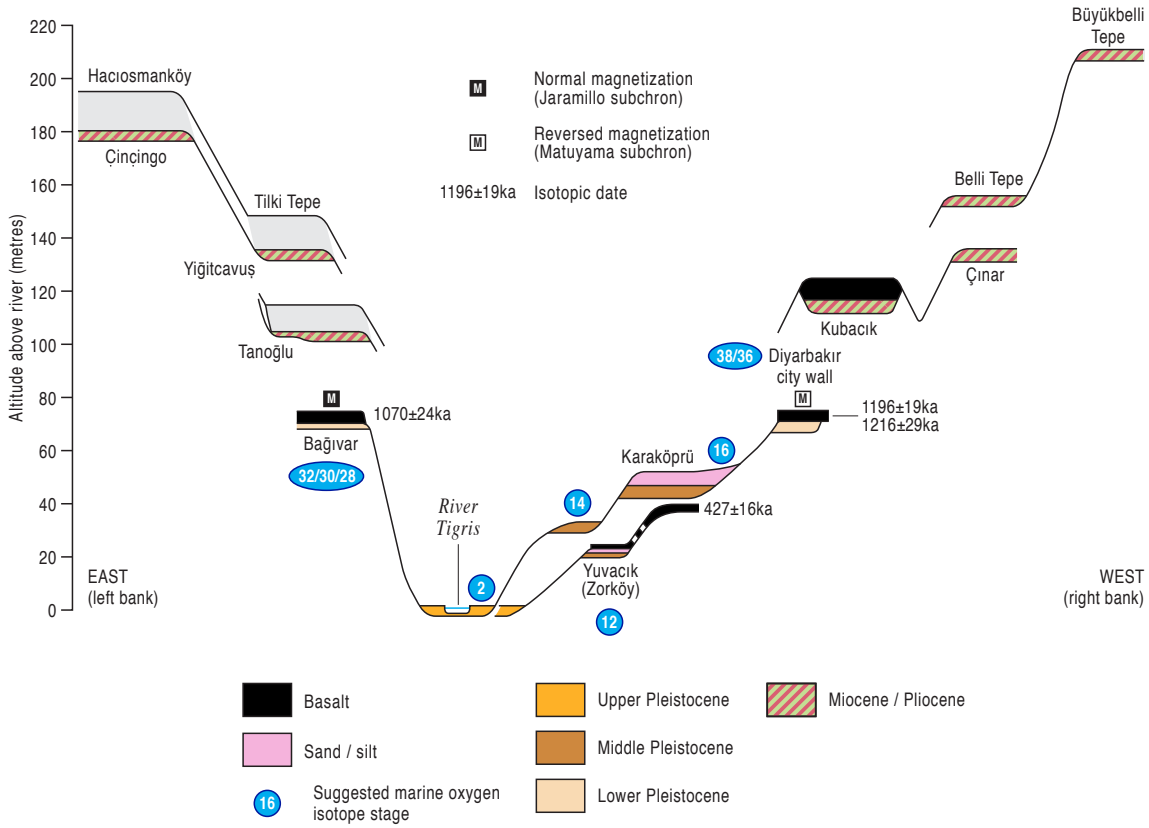

Altitude above river (metres)
220
200
180
160
140
120
100
80
60
40
20
0
EAST
(left bank)
WEST
(right bank)
Hacıosmanköy
Çınçingo
Tilki Tepe
Yiğitcavuş
Tanoğlu
Bağıvar
32/30/28
1070±24ka
River
Tigris
2
14
Karaköprü
16
427±16ka
Yuvacık
(Zorköy)
12
38/36
Diyarbakır
city wall
1196±19ka
1216±29ka
Kubacık
Belli Tepe
Büyükbelli
Tepe
Çınar
M
Normal magnetization
(Jaramillo subchron)
Reversed magnetization
(Matuyama subchron)
1196±19ka
Isotopic date
Basalt
Sand / silt
Suggested marine oxygen
isotope stage
Upper Pleistocene
Middle Pleistocene
Lower Pleistocene
Miocene / Pliocene

Figure 7

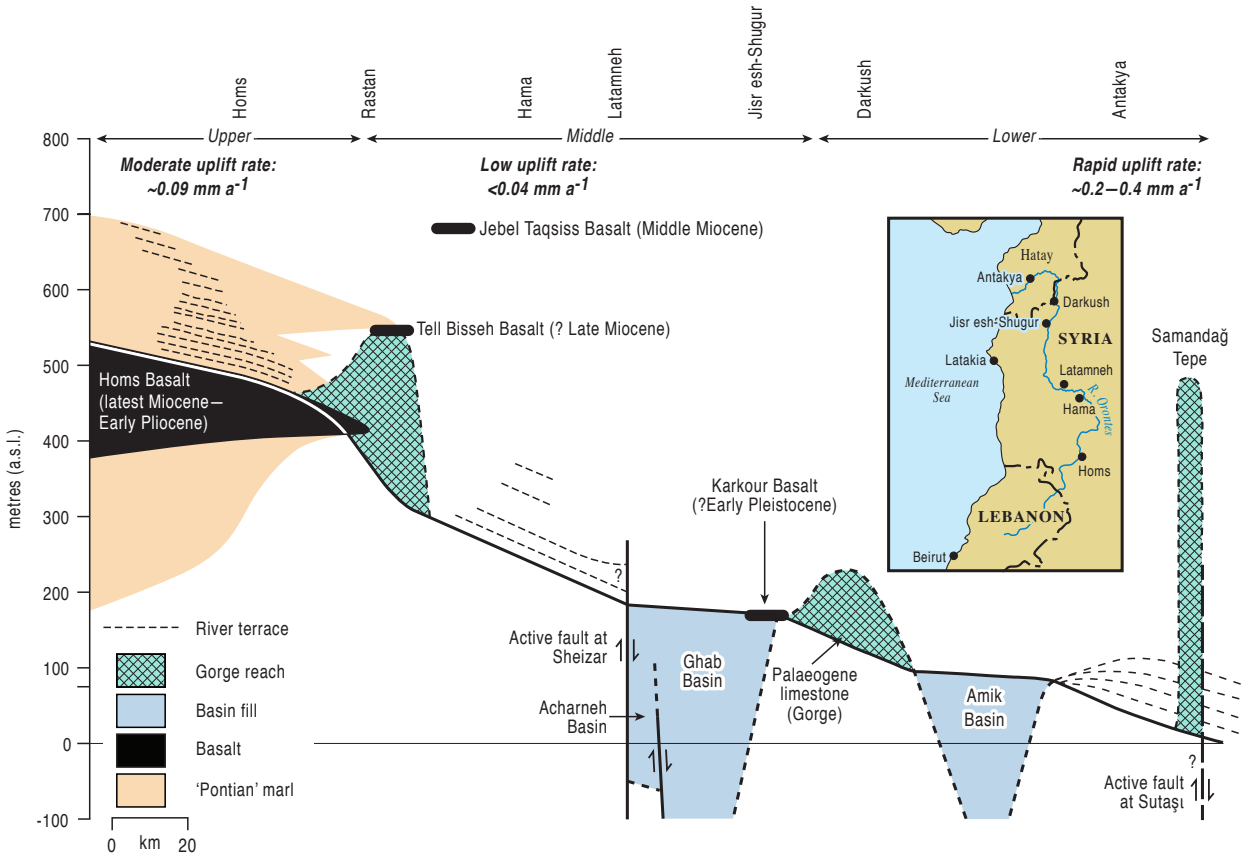

Homs
Rastan
Hama
Latamneh
Jisr esh-Shugur
Darkush
Antakya
Upper
Middle
Lower
Moderate uplift rate:
~0.09 mm a-1
Low uplift rate:
<0.04 mm a-1
Rapid uplift rate:
~0.2–0.4 mm a-1
Jebel Taqsiss Basalt (Middle Miocene)
Tell Bisseh Basalt (? Late Miocene)
Homs Basalt
(latest Miocene–
Early Pliocene)
Karkour Basalt
(?Early Pleistocene)
Samandağ
Tepe
metres (a.s.l.)
800
700
600
500
400
300
200
100
0
-100
River terrace
Gorge reach
Basin fill
Basalt
'Pontian' marl
0 km 20
Active fault at
Sheizar
Acharneh
Basin
Ghab
Basin
Palaeogene
limestone
(Gorge)
Amik
Basin
Active fault
at Sutaşı
Hatay
Antakya
Darkush
Jisr esh-Shugur
SYRIA
Latakia
Mediterranean
Sea
Latamneh
Hama
R. Orontes
Homs
LEBANON
Beirut

Figure 8

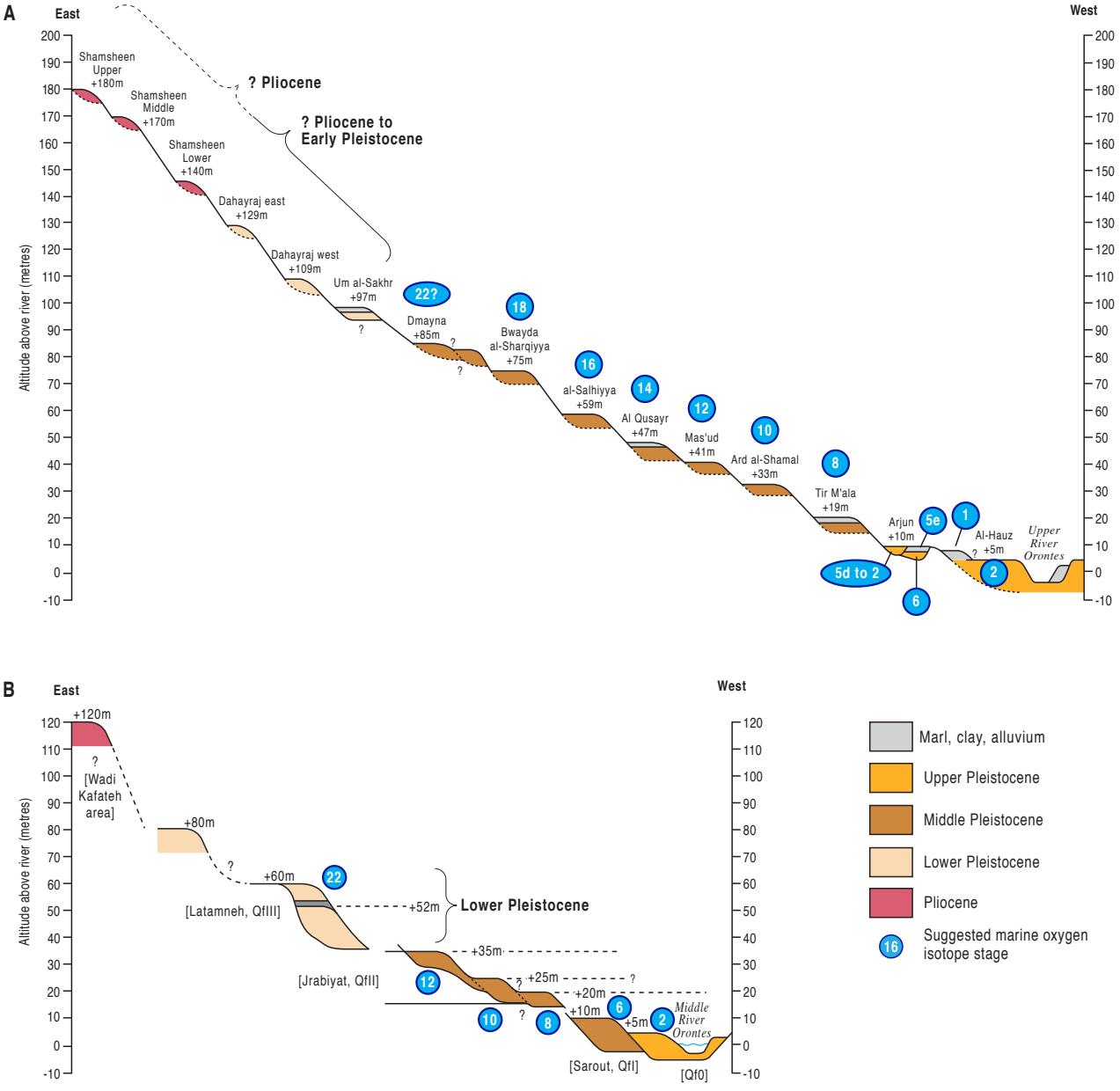

A
East
West
Altitude above river (metres)
Shamsheen Upper +180m
Shamsheen Middle +170m
Shamsheen Lower +140m
Dahayraj east +129m
Dahayraj west +109m
Um al-Sakhr +97m
? Pliocene
? Pliocene to Early Pleistocene
22?
Dmayna +85m
18
Bwayda al-Sharqiyya +75m
16
al-Salhiyya +59m
14
Al Qusayr +47m
12
Mas'ud +41m
10
Ard al-Shamal +33m
8
Tir M'ala +19m
Arjun +10m
5e
1
Al-Hauz +5m
Upper River Orontes
5d to 2
2
6
B
East
West
Altitude above river (metres)
+120m
[Wadi Kafateh area]
+80m
+60m
22
[Latamneh, QfIII]
+52m
Lower Pleistocene
[Jrabiyat, QfII]
+35m
+25m
+20m
+10m
+5m
12
10
8
6
2
Middle River Orontes
[Sarout, QfI]
[Qf0]
Marl, clay, alluvium
Upper Pleistocene
Middle Pleistocene
Lower Pleistocene
Pliocene
16
Suggested marine oxygen isotope stage

Figure 9

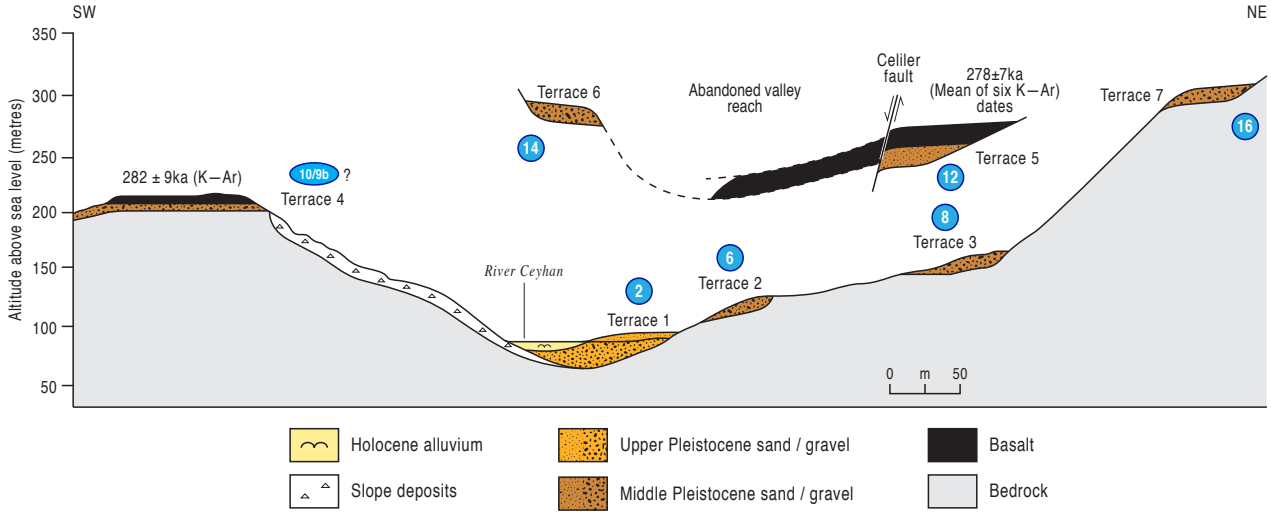

SW
NE
Altitude above sea level (metres)
350
300
250
200
150
100
50
282 ± 9ka (K–Ar)
10/9b
?
Terrace 4
Terrace 6
14
Abandoned valley reach
Celiler fault
278±7ka (Mean of six K–Ar) dates
Terrace 5
12
8
Terrace 3
Terrace 7
16
River Ceyhan
2
Terrace 1
6
Terrace 2
0 m 50
Holocene alluvium
Slope deposits
Upper Pleistocene sand / gravel
Middle Pleistocene sand / gravel
Basalt
Bedrock

Figure 10

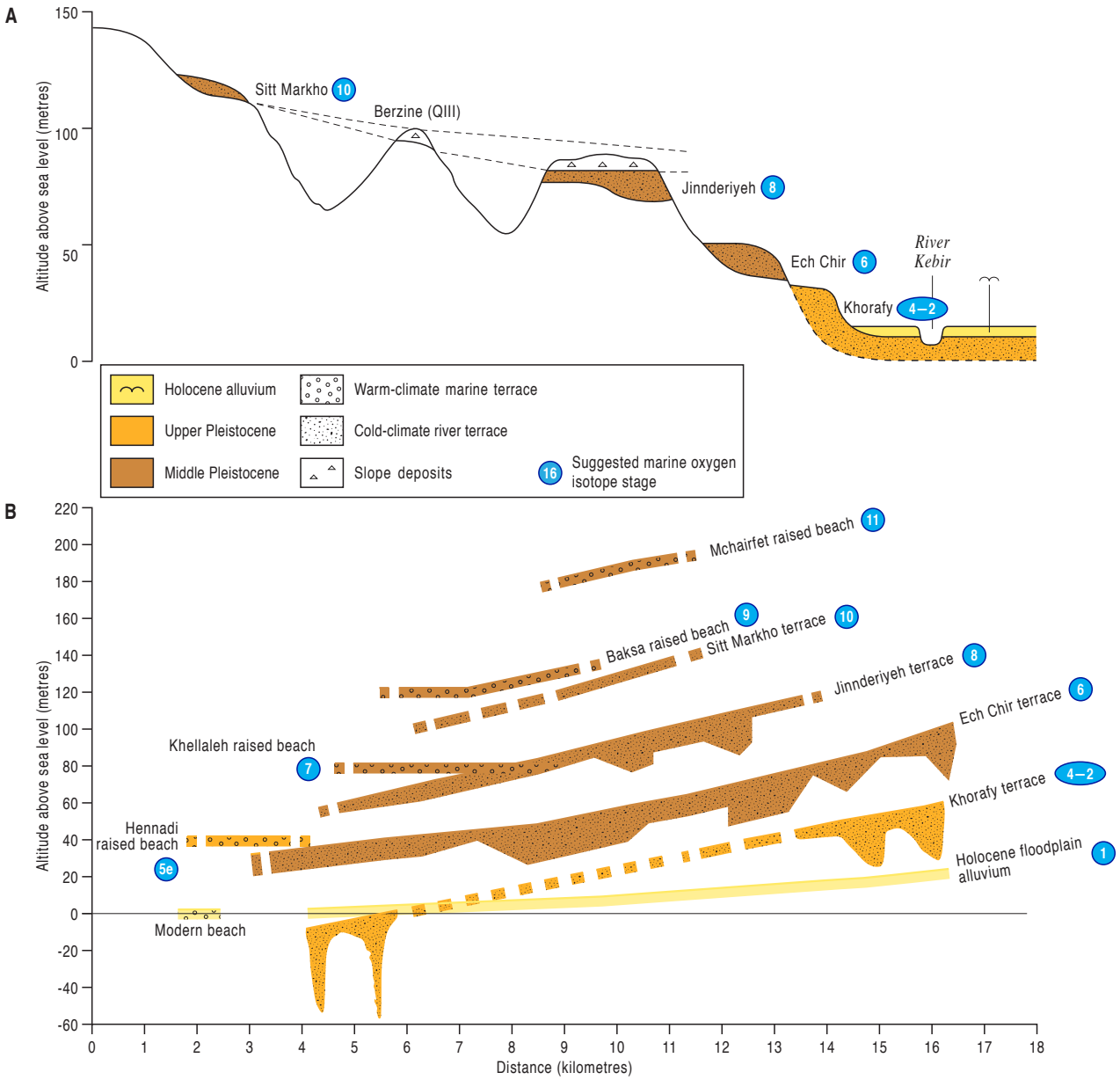
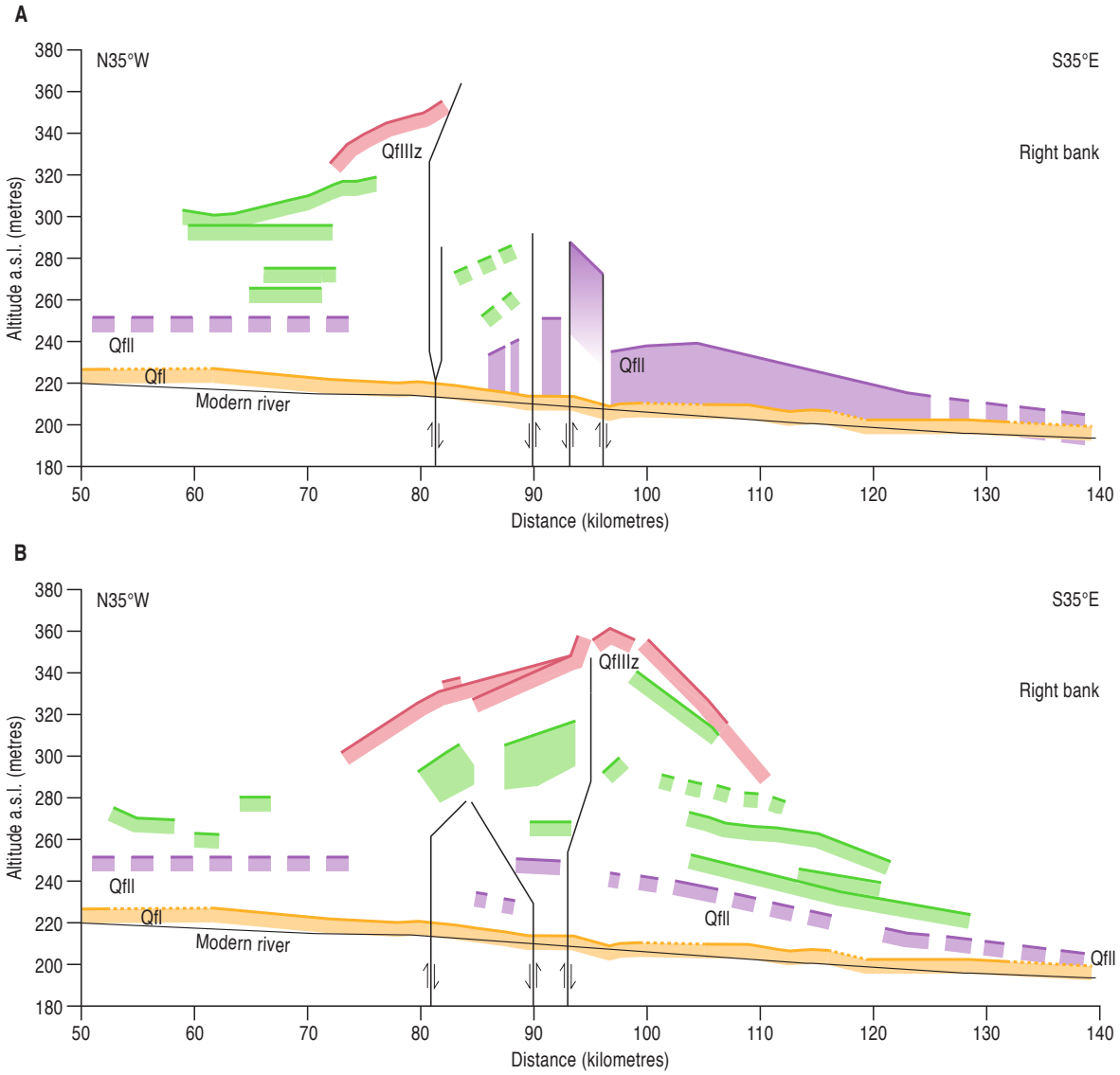

A
Altitude above sea level (metres)
150
100
50
0
Sitt Markho 10
Berzine (QIII)
Jinnderiyeh 8
Ech Chir 6
River Kebir
Khorafy 4–2
Holocene alluvium
Upper Pleistocene
Middle Pleistocene
Warm-climate marine terrace
Cold-climate river terrace
Slope deposits
16 Suggested marine oxygen isotope stage
B
Altitude above sea level (metres)
220
200
180
160
140
120
100
80
60
40
20
0
-20
-40
-60
Mchairfet raised beach 11
Baksa raised beach 9
Sitt Markho terrace 10
Jinnderiyeh terrace 8
Ech Chir terrace 6
Khellaleh raised beach 7
Khorafy terrace 4–2
Hennadi raised beach 5e
Holocene floodplain alluvium 1
Modern beach
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Distance (kilometres)

Figure 11


A
N35°W
S35°E
Right bank
QfIIIz
QfII
Qfl
Modern river
QfII
Altitude a.s.l. (metres)
380
360
340
320
300
280
260
240
220
200
180
50
60
70
80
90
100
110
120
130
140
Distance (kilometres)
B
N35°W
S35°E
Right bank
QfIIIz
QfII
Qfl
Modern river
QfII
QfII
Altitude a.s.l. (metres)
380
360
340
320
300
280
260
240
220
200
180
50
60
70
80
90
100
110
120
130
140
Distance (kilometres)

***Highlights (for review)**

Climatic fluctuation has forced river-terrace formation in the Mediterranean region

Climatic forcing has been over-printed onto the effects of background regional uplift

Differing patterns of fluvial-archive preservation reflect distinct uplift histories

Disparate uplift histories correlate with crustal type and mobility of lower crust

The effects of Quaternary tectonic activity are seen in the deformation of terraces

RESPONSE TO REVIEWS – This has been added to this document, which is the e-mail from the Guest Editor (including the review summaries), using colour-coded highlighting and comments boxes. There is also information about revisions made in the colour-coded annotated manuscript, which will be supplied as part of the revision, in addition to a clean copy.

Reviewers' comments:

Dear David,

Apologies for the delay in finding suitable and available reviewers for this paper. We now have two completed reviews. Having looked at the submitted paper myself and the comments of the two reviewers, I am sending this paper back to you for major revision, including significant structural changes. I would like to see you address the detailed comments of both reviewers and specifically to undertake the following changes:

1. The key issue with this paper as it currently stands is the lack of a single focus, as commented on by both reviewers. It seems to me that the simplest way to create focus in this paper is to use the four crust types that you refer to in the discussion as a structure for the entire paper. There is no citation given for these, so maybe it is a new idea? Either way, these could be set out either as a new idea or referring back to the original citation in the introductory sections of the paper. Then, these crust types could be used to structure the descriptions of the river systems in the middle parts of the paper. I think that a comparative table or figure would be useful to highlight the key different features of sequences in these different crustal regions.
2. The description of Black Sea sequences sits strangely in the Discussion. If you want to include these sequences, they should be described earlier on, and the scope of the study area broadened. If you want to stick to the study area specified, then you should remove mention of these sequences, except very briefly if necessary, without accompanying Figures, and be content with an incomplete record of the four crust types that you outline.
3. Please standardise the terrace descriptions presented. At present these read as half way between a summary and a complete description. Is this because you are updating some interpretations for these records? It is not clear in the text. Also, it feels like the information being presented for each region is slightly different. The key issues to address for each sequence seem to be whether these are cold stage deposits, what the age control is, and what evidence if any there is for external driving controls - see detailed notes from reviewers. Please make sure each sequence has the same information presented from it.
4. Please go into greater depth in the Discussion about the implications from these sequences about tectonic influences and the temperature / humidity debate. This was noted by both reviewers.
5. Both reviewers note concerns with the text discussing numerical modelling of such systems. Please address this. In particular, please engage constructively with the literature that is critical of the Westaway model and make your discussion of stream power law models more relevant to the points being made in that section of the paper, or remove it.

I look forward to receiving your revised manuscript soon.

Best wishes, Becky

Reviewer #1: Review JQSR -D-16-00142
Drivers of river-terrace formation in the NE Mediterranean region: evidence from Syria and Turkey.
By Bridgland et al.

Comment [DRB1]: Following this advice the paper has been restructured to emphasize the patterns of archive occurrence in relation to crustal types. Indeed, we have changed the title to reflect this emphasis.

Comment [DRB2]: One of the four key crustal types is not found in the study area, so we have opted to retain the Black Sea region as a comparison area. The diagram is required for that purpose. Given that we have (following editorial guidance – see Comment 1) concentrated the emphasis of the paper on archive preservation patterns in relation to crustal type, this seems sensible. Nonetheless, we have elected to do much of what is suggested here – moving the N Black Sea to form a part of the introduction. This is an exemplar area, researched in great detail by Soviet workers and thus is useful as a point of comparison. Following the advice from the reviewing process we have reversed things so that we establish the Black Sea early on and then compare our archives with it.

Comment [DRB3]: This is a somewhat tall order, as each sequence has different characteristics and quality/types of evidence, as we had tried to show. We have based each case-study area around illustrations, using text enough to get the main points across. Comments like these are non-specific, so it is difficult to know exactly what is thought to be wrong with what we have produced. We have beefed up some descriptions and slimmed some down, but we didn't really see any big difference in the first place.

Comment [DRB4]: We had already provided a full section on tectonic influences and, indeed, a discussion of the humidity versus temperature debate. We have sought to reinforce and emphasize the key points in these sections.

Comment [DRB5]: We have edited the text to be more circumspect about the uplift Modelling (Westaway model) but are not aware of any literature that specifically criticizes it (it has generally been ignored rather than criticized). The power law stuff has been deleted. A cross reference to the Demoulin et al. paper in this present special issue will be a helpful addition here, since that paper discusses this issue.

When I read this paper I became somewhat disappointed by its content. The factual evidence is discussed in a very general way without really touching the details that matter and sometimes almost tending towards circular reasoning. The latter refers to the use of the lower crustal model to infer ages, but it appears that cold stage deposition is part of the model, because an "European" correlation is used.

In general I find the focus of the paper to be unclear. Is it about drivers of terrace formation or is about the specific terrace sequences in Syria and Turkey or is it about 4 patterns of terrace record preservation?? I suggest to limit the scope of the paper to terrace formation drivers of the northern Arabian Platform only.

Much of what is discussed appears to have been published before, giving the suggesting that this paper is actually a kind of review. The best developed part of the paper are the illustrations how different tectonic regimes affect the terrace record expression and preservation. The role of base level and climate are much less well developed.

What I find lacking, are more detailed descriptions of the evidence that terrace/gravel bodies are indeed cold stage depositions? And the properties of the coastal terraces, are they indeed raised beaches?? More info or photo's on sedimentary architecture and deposits is strongly recommended. For example are there paleosols or other environmental indicators? The cold stages in the Mediterranean were not really cold (with permafrost) in the studied area, they were cooler and probably drier. Could you give the reader some climate proxy info such as sapropel and oxygen isotope and pollen curves? I strongly suggest to include the PPP paper (see below) where one of the co-author is also co-author. In this paper both the role of temperature and wetness are discussed in the Early Pleistocene in contributing to terrace formation in western Turkey. It turns out that environmental and landscape stability played a key role in triggering Early Pleistocene terrace formation in this part of Turkey.

I see no added value (only confusion) to introduce in the discussion new descriptions of the system dynamics of rivers draining into the Black Sea. It seems to be there to introduce a pattern of terrace record development and preservation which is absent in the target areas in Syria and Turkey. I strongly suggest to leave this out. It only distracts from the overall line of reasoning.

More specific remarks:

Abstract:

What do you mean with optimal development in the first sentence?

Could you make it clear in the abstract if this paper presents new data or simply is a review?

Please specify or quantify what is meant with rapid uplift.

Your last sentence in the abstract is in my view not substantiated in the text. When I look at Fig 9 I seen tilted raised beaches parallel to the fluvial gravels. From this figure I deduct also that these older raised beaches contain gravels? Doesn't this contradict the interpretation?

Especially the stage 9 labelled raised beach suggest in my view the opposite, high stand (is warm stage) deposition of beach gravels!! Please discuss this more elaborately! In the text no detailed supportive argumentation is given to correlate the terrace deposits to cold stages. In Europe we have several indicators of cold stage deposition that are not evident in the studied area.

Introduction: as you must be aware is the lower crustal flow model contested. It is therefore important to take the alternative models more seriously, and not simply discard them.

The fluvial record section should strive to separate real observations from model derived estimated age estimations. I get the impression that of several terraces sequences only one or two real hard age estimates exist. As we all know does any curve fit one point and most curves two points. The lower crustal flow model produces an uplift curve but with less than 3 fixed points in altitude and

Comment [DRB6]: This is justified on the basis that the river terraces and coastal terraces in the Latakia area are interwoven just as in southern England. We have attempted to reinforce the discussion of this. Given the paucity of fossils and the absence of Quaternary perglaciation in lowland parts of this region, there is little evidence that can be brought to bear on this issue from the inland parts of the region (as our text now states).

Comment [DRB7]: This has already been addressed in response to the Guest Editor's suggestion.

Comment [DRB8]: Of course it is a review!

Comment [DRB9]: This reflects the main thrust of the paper and has been further emphasized in the revision and the altered title, which is now a better reflection of the content.

Comment [DRB10]: Much of this depends on the Kebir, as is pointed out in appropriate parts of the paper. Sections on this have been beefed up; the credentials of the raised beaches can be established from fauna etc., as was achived by the Russians when working in the area.

Comment [DRB11]: Beefed up

Comment [DRB12]: Added

Comment [DRB13]: We disagree – there is an important comparison to be made and the existence of the zero-uplift example is important. We have, however, restructured the paper and moved this exemplar area to the introduction??

Comment [DRB14]: Optimal means 'best'

Comment [DRB15]: We make it clear that this is a review at the end of the Introduction. This does not seem necessary in the abstract, given that the journal title includes the word 'reviews'

Comment [DRB16]: This is explained in the paper and does not need to be in the abstract.

Comment [DRB17]: The rising of the marine terraces inland is caused by an increase in uplift rates moving inland, as is now stated in the enhanced figure caption.

Comment [DRB18]: We are not aware of alternative models that attempt to explain the patterns observed. Rather than contest the lower crustal flow hypothesis most other authors have ignored it. However, the Veldkamp and Demoulin et a papers in this special issue, which also add to debate on these topic, are both cross referenced. We have generally sought to use more equivocal language when dealing with the 'lower-crustal flow model'.

time could many alternative curve/model be equally valid! I therefore propose to clearly indicate in all figures which age correlations are evidence (fossils or Ar/Ar) based and which ones are model derived.

A general underlying assumption of the uplift modelling is a kind of equilibrium between uplift rate and incision rate. This seems a reasonably assumption, though for the extreme high incision values (> 0.2 m/ka of the > 0.5 m/ka for the lower River Ceyhan) this might (most probably) not hold true anymore!!! Please be aware that high uplift rates only generate strath terraces where the equilibrium assumption is not valid anymore. Furthermore, is the change for terrace preservation very limited. That is why gorges do not yield an uplift record.

I am intrigued by the spatial pattern that the northern Arabian Platform yields. The reconstructed tectonic inversion does call in my view also for a plate tectonic trigger or driver. Please elaborate on this issue.

4.3 the earlier referred paper should be used:

A. Veldkamp a, I. Candy , A.G. Jongmans, D.Maddy, T. Demir, J.M. Schoorl, D. Schreve, C. Stemerdink, T. van der Schriek,. 2015. Reconstructing Early Pleistocene (1.3 Ma) terrestrial environmental change in western Anatolia: Did it drive fluvial terrace formation? Palaeogeography, Palaeoclimatology, Palaeoecology 417 (2015) 91-104.

It indicates periods of landscape stability during the warm and cold stages, and landscape instability in between with large scale erosions and sediment generation. This study suggest that during the early Pleistocene the warm (and wet) and cold (and dry) stages no terrace deposition took place (limited sediment and/or water available). During the climate induced environmental transitions, sediments were generated from the landscape that may have ended up in the terrace sediment bodies. It indicates that the proposed mechanism in the paper is too simplistic for the earlier Pleistocene. Please do not forget that periglacial processes where not that important in the studied areas as in NW Europe.

In general is the conclusion section too long. It requires a clear focus on the message and a strong punchline in the end to bring the main message across.

Sometimes symbols are used in the the figures that are not explained in the text or captions

Overall I can only recommend a major revision of this potentially interesting and relevant paper.

Tom Veldkamp

Comment [DRB19]: I thought that we had added dating points clearly enough in the diagrams. We have added more clear-cut emphasis on the use of the modelling to 'fill the gaps' between the 'pinning pointsprovided by the dates.

Comment [DRB20]: The reviewer holds views that we do not entirely agree with (i.e, on stream power law). However, because this is dealt with in another paper in the special issue (Demoulin et al.) we have removed the section of this paper that discussed that topic (which was criticized by the referees). We have, however, addressed the comment about gorges

Comment [DRB21]: Should be chance? Otherwise we do not understand this one. We have mentioned gorges??

Comment [DRB22]: Gorges don't yield an uplift record because they don't have terraces!

Comment [DRB23]: We do not believe this is tectonic – we see this in many areas that are not close to plate boundaries. All this is explained in this paper (and in our earlier [cited] work).

Comment [DRB24]: The conclusion section has been rewritten to take account of the revision of the paper and the new emphasis on the preservation patterns in relation to crustal type. It is only 549 words.

Comment [DRB25]: There has been an overhaul of figures and legends – we were aware of some issues, as several were compiled from previous publications. We hope to have eliminated all such problems.

Reviewer #2: Review of JQSR-D-16-00142. "Drivers of river-terrace formation in the NE Mediterranean region: evidence from Syria and Turkey". David R. Bridgland, Tuncer Demir, Ali Seyrek, Mohamad Daoud, Mohammad Abou Romieh, Rob Westaway.

This paper synthesizes and discusses the most recent work by the authors on fluvial archives in SE Turkey and Syria, in which they have been working for quite some years now. It is an enjoyable read and a valuable contribution in the sense that it aims to set fluvial evolution in the region in a broader structural context. The paper describes and synthesizes fluvial development of rivers cross -cutting several major tectonic units in the region. The authors argue for similar fluvial terrace development of different rivers on the same tectonic unit, driven by, after the Mid-Pleistocene Revolution, 100 ka cycles. They distinguish different structural blocks which each have their own uplift regime. Finally, they summarize 4 principal types of fluvial archive preservation and compare those in the Arabian Platform with rivers north of the Black Sea, indicating how this structural influence on fluvial development crosses climatic zones.

The described general pattern is intriguing. Especially where a single river cross-cuts these structural boundaries (e.g. The Orontes) and changes its "archive type" to an adjacent river on the same crustal block. However, the way in which the case is made at the moment, both in conveying their observational evidence for this pattern as well as discussing alternatives, needs revision.
In the annotated PDF, I have included textual remarks, as well as 'scientific' comments. I will summarize these in some main points below. Note that I cannot refer to line numbers here, as the manuscript unfortunately does not contain them.

* In general, the authors interpret all presented river terraces as associated with 100 ka climate cycles and regional uplift. Uplift-driven incision is of course a widely accepted phenomenon, but the case has to be made for each individual river separately, given the highly variable landscape and structural behaviour of the region. Although I understand that the research is already conveyed in the cited papers, I would strongly suggest to spend more words on why it is exactly the proposed structural uplift-incision relation that is causing fluvial incision in every stated case, and not any other mechanism (e.g. local perturbations such as drainage diversion, active faulting, and transient response of river systems to these drivers, as the authors do report that these drivers do/did occur). I am however not saying that the mechanism is not plausible, but I would like to see a stronger argument towards this mechanism for each separate case if possible, or discussion on potential indications of influence of the other drivers. Several remarks in the annotated pdf relate to this point.

* I am aware of the limitations of the stream power law (and its strengths). The discussion of the stream power law in the discussion section, however, could in my view be a bit more to the point, more connected to the paper, as now it stands a bit on itself. Now, the authors first state that their proposed mechanism is incompatible with the stream power law. Subsequently, they critically discuss some limitations, or assumptions/boundary conditions, of the stream power law. But I then miss how this is incompatible with their proposed mechanism. Now it appears to be only some criticism on the stream power law. See further comments in the annotated pdf.

All in all I think this would call for a minor/moderate revision.
Annotated pdf attached.

Comment [DRB26]: Attended to with reference to the annotated pdf.

Comment [DRB27]: A slightly oversimplified statement, as some reaches of some rivers might show terraces only in relation to a longer periodicity – see the end of section 2.1, where terrace formation in relation to Kukla 'supercycles' is suggested for the Euphrates.

Comment [DRB28]: It seems wrong-headed to seek individual explanations (such as drainage diversions) for phenomena that are seen over broad areas. This is what is wrong with interpretations based on single sites or single systems without sight of the bigger picture. Nonetheless we show what perturbation in response to tectonic activity looks like, as also illustrated in Fig. 11; we also make take into account changes in fluvial course length, where this is known to have occurred (Euphrates).

Comment [DRB29]: The stream power law approach is no longer mentioned as such; the companion paper by Demoulin et al., which is now cross-referenced, provides an extensive debate about this approach and attempts to reconcile it with terrace evidence.

Reviewer attachments (if any):
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