# Rift Shoulder Source to Prodelta Sink: The Cenozoic Development of the Nile Drainage System*

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## Introduction

This paper reconstructs the Oligocene to Recent Nile drainage system in a manner that honours both onshore and offshore evidence for the history of the river system. Source-to-sink relationships are investigated by integrating evidence and data on sedimentation rates and volumes, seismic facies, quantification of denudation (AFTA), topographic features, and palaeoclimatic analysis. Although there is a voluminous literature on the history of the Nile, this is the first attempt to integrate the crucial offshore evidence.

## Previous Work and Onshore Evidence

### Previous Work and Landform Analysis

There is a considerable volume of literature concerning the geological history of the River Nile, which is based primarily on onshore geological and geomorphological evidence. Previous interpretations fall into two groups, The first group has been led by Egyptian workers (Said, 1981; Issawi and McCauley, 1992), who, from the study of landform analysis including radar studies, believe an extended Nile did not connect from Ethiopia and Sudan through to the Mediterranean until at earliest Late Messinian times. Other authors, e.g. Burke and Wells (1989), favour a model by which the Blue Nile and other Ethiopian tributaries (Figure 1) originated in the Oligocene and followed a similar course through Sudan to Present day and an uncertain course through Egypt to reach the current outlet. All authors seem agreed that, on the basis of the lack of Nilotic biota until 0.5Ma in Lake Albert (Pickford et al, 1994) and of the thickness of lacustrine sediments in the enclosed Sudd basin of Sudan (Salama,1997), the White Nile (Figure 1) is a recent river. Even now, due to sediment deposition and evaporation in the Sudd swamps, there is only a minor sediment contribution from the White Nile reaching the confluence at Khartoum (Said, 1981; Shukri, 1949).

Egyptian outcrop geology and landforms are well documented and seem to evidence a differing course of rivers prior to the Messinian. Issawi and McCauley (1992) document two major systems, the Oligocene-early Miocene ‘Gilf’ system, which drained the developing Red Sea rift shoulders towards the Western Desert, turning north to join a’ channel system and outlet documented by Dolson et al. (2002), and the early to mid Miocene 'Qena' system, which drained most Egyptian rivers of that age southwestwards into Nubia, and possibly westwards into Chad (Figure 1). While the evidence presented for this river course as far south as the Egyptian-Sudan border is persuasive, the evidence for the continuation into Chad is poor, and is re-examined here. The Plio-Pleistocene history of the Nile is well documented in the seminal publication of Said (1981).

Essentially, therefore, the disagreement between the two groups of authors can be summarised to be whether a north-flowing pre-Messinian 'Blue Nile' plus joining tributaries from southern Egypt reached the Mediterranean through a course crossing the Western Desert or was diverted westwards into Chad and to an eventual outlet in the Niger. This disagreement is examined below by study of offshore sedimentation rates in both the Nile and Niger.

## Palaeoclimatic Data and Variations (Figure 2)

The Present-day Nile river system demonstrates strong climatic and topographic controls, with over 90% of current sediment originating from the seasonally wet Ethiopian rift shoulders (Shukri, 1949). This sediment is very shale-prone as the eroding material in Ethiopia consists largely of trap basalts. This pattern is, however, only indicative of the current unusual hyperarid conditions affecting the hinterland, dating from at earliest, the initiation of the Sahara at 2.5Ma (Said, 1981; Burke and Gunnell, 2008), though even in that period, there have been distinct wetter periods. There is abundant palaeoclimatic data indicating that the Nile catchment experienced much wetter conditions over most of the Oligocene to Pliocene period. Particularly, wet phases evidenced in the geological record include the early Pliocene, when sedimentation rates in the Nile Cone were at a maximum (Said 1981, Figure 2), the Tortonian, when a wide-ranging mammalian fauna is known to have lived in the Present-day Western Desert (Pickford et al. 2006), and the early Miocene and Oligocene, both represented by evidence for 'fossil forests' in Western Desert strata (Said, 1981). These periods do, however, seem to have oscillated with periods of drier and possibly Sahara-like conditions, when ferricrete soils were developed in Sudan (Schwartz and Germann,1980) and evaporites were deposited in the Red Sea and Mediterranean. Examination of outcrop geology would predict that wet-phase sediment would be more sand-prone than during dry periods, with more erosion of granitic material on the Red Sea rift shoulders and of the outcropping Nubian sandstone within southern Egypt and Sudan. Under this model, sands would have preferentially entered the Nile shelf during the wetter periods, perhaps corresponding to glacial highstands when the Intertropical Convergence Zone was situated farther north and were later reworked into deep water during lowstands.

## Thermochronological Data (Figure 3)

Most authors agree that the Red Sea Hills are a major source of Nile sediment (e.g., Burke and Wells, 1989), representing the only significant area of the catchment where there has been both major uplift and deep erosion into Basement. The structural history of this region is summarised by Bosworth et al. (2005), who interpret that uplift of the rift shoulders commenced around 27 Ma and peaked around 20Ma. The occurrence of late Oligocene gravels overlying the Egyptian limestone plateau confirm an Oligocene date for the initiation of Red Sea uplift. Farther south the Afar Swell is thought to have been initiated at earliest Oligocene (circa 31 Ma, Burke and Gunnell, 2008).

In comparison to other regions of Africa, the Basement of the Red Sea Hills has been heavily analysed with Apatite Fission Track (AFTA) analysis. Of some 111 points measured between Sinai and Eritrea (Kohn and Eyal, 1981; Ghereab et al., 2002; Omar and Stecker, 2005), just under half have fission-track ages of Tertiary and about a third of Oligocene or younger age. This is the only such dataset in Africa in which such young ages are commonly seen. The fission-track ages measure the time at which the rocks concerned last cooled below a temperature of circa 110 deg C, which under current geothermal gradients in the region (circa 40 deg C/km), would imply that circa 2000m of overburden have been removed since that time. Because about a third of the samples then suggest that a 2000m or greater overburden existed at Oligocene time, while the other two-thirds suggest a lesser overburden than this, then an average eroded overburden of 1.5 km over the Red Sea hills as a whole seems a reasonable estimate.

AFTA analysis has not been made over other parts of the hinterland, although Pik et al. (2003) have undertaken an Apatite-Helium age study over the Blue Nile and Tekeze gorges; it concludes, on the basis of partial resetting of these Apatite-He ages, that erosion of the gorges commenced at 25-29 Ma.

### Erosional Analysis – Other Areas

Assessments of volumes eroded in the Blue Nile and Tekeze catchments of the Ethiopian Highland have been made by Pik et al. (2003), by subtracting the present topography from the extrapolation of Oligocene or plateaux/erosion surfaces. Over the studied area, the plateaux are capped by flat-lying Oligocene trap basalts, and Pik et al. have calculated an average of 860m erosion. Over much of Sudan, hilltops are capped by what is believed to be an uplifted erosion surface of pre-Oligocene age (Whiteman, 1971). Differences in topography between the plateaux and plains are minor here, at most a few hundred metres; so the average erosion is believed to be small, but further field analysis would be required to calculate an exact figure. Over the Darfur Swell, Eocene volcanics remain in outcrop, suggesting little erosion. Erosion over the outcrop of the Nubian Sandstone in northernmost Sudan and southernmost Egypt seems also to be no more than a few hundred metres according to cross-sections in hydrogeological studies (e.g., Gossel et al., 2004). Over most of Egypt itself, erosion of Eocene and Upper Cretaceous limestones is slowly continuing by scarp retreat, giving no significant clastic contribution.

## Offshore Evidence

### Red Sea (Figure 3)

An independent estimate of average erosion over portions of the Red Sea Hills can be obtained by comparing sediment volumes in depocentres offshore Red Sea with the areas of drainage catchments supplying them, assuming these have remained relatively constant with time. This has been attempted here for the Halaib and Tokar depocentres, using a post-evaporite isopach map of Mitchell et al. (2007) (Figure 3). According to the stratigraphy of Bosworth et al. (2005), this covers the period of 10Ma-Recent. Sedimentation volumes calculated remove all porosity, using a porosity-depth trend from Sclater and Christie (1980), a North Sea compilation used frequently by basin modellers, assuming an average lithological content of 90% shale and 10% sand. Dividing the calculated compacted sediment volume by the areas of the catchments gives an average erosion value of 400m for the Halaib catchment and 900m for the Tokar catchment. Since the period of 0-10Ma covers about a third of the erosional period of the rift shoulders, and about half the sediment volume seen in the Nile Cone, these figures are fairly consistent with an average erosion figure over the Red Sea Hills of about 1.5km.

**Nile Delta and Cone**

Compacted sediment volumes in the Nile Cone are calculated, using the same methodology as described above, from two isopach maps covering the Plio-Pleistocene (Figure 4) and Oligocene to Miocene (Figure 5) periods. The former is well controlled by a number of previously published maps, of which the most detailed is that of Hall et al. (2005), and is controlled at key locations where there is knowledge of the isopach from drilling, such as the Abu Madi area of the Nile Delta. The Oligocene-Miocene isopach map is a new compilation that has been compiled from a variety of published sources which include 1) published structure and isopach maps in the Levantine Basin of Gardosh et al. (2009) and Steinberg et al. (2011), 2) addition of a series of published isopach maps of Abdel Aal et al. (1993) over the shallow-water Nile Delta area, and 3) contouring round isopachs measured from a number of published cross-sections over regions farther west and offshore (Dolson et al., 2000; Abdel Aal et al., 2001; Cross et al., 2009; Gardosh et al., 2009; Kellner et al., 2009). The two maps show very different architectures, with the Plio-Pleistocene seemingly unconstrained by tectonics and showing a typical 'delta' shape, while the Oligocene-Miocene isopach shows two distinct lobes extending out into the Herodotus and Levantine basins, separated by a thin corresponding to the Rosetta-Erastothenes High. These two lobes are the likely locations of distal basin-floor sheet sands, such as have recently been reported from the Tamar and Leviathan discoveries in the Levantine Basin. The thickest section of the delta or cone is the Damietta depocentre (Figure 5), which has up to 9km of Oligocene-Recent fill, including a particularly thick Oligocene (J. Craig, pers comm.), marking where the Nile outlet must have been at that time.

These maps give estimates for total volumes of $1.88 \times 10^5$ $km^3$ for the Plio-Pleistocene and $3.86 \times 10^5$ $km^3$ for the Oligo-Miocene. These include small volumes input from other river systems, particularly the canyon systems of SE Israel, though the overall isopach shapes do not suggest that these are significant. As discussed in Steinberg et al. (2011), it is likely most Levantine deepwater sediment derives from the Nile.

Offshore and onshore Nile Delta seismic data both evidence a major change in sedimentary facies over a major unconformity close to the Eocene-Oligocene boundary (Figure 2). Dolson et al. (2002) illustrate a major downcutting unconformity over the offshore Herodotus Basin that correlates with a change from carbonates to channelized clastics onshore, while a seismic section offshore Levantine Basin in Gardosh et al. (2009) appears to show downlaps over the same unconformity. These features are thought to tie to initiation of the Nile drainage system.

**Nile and Niger Comparison** (Figure 6)

Authors such as Goudie (2005) and Issawi and McCauley (1992) have proposed that the Niger originally had a much larger catchment than Present day which covered much of the Present-day Nile catchment. This interpretation of a 'Trans-Africa Drainage System' is supported here for the Palaeocene-Eocene section (Figure 7), where offshore African sedimentation is dominated by the Niger, suggesting that the

Niger system captured headwaters from much of Africa at the time (Macgregor, 2010, first map on Figure 7). The comparison of sedimentation rates in the two depocentres (Figure 6), as measured from a number of published cross-sections, suggests a shift in sedimentation from the Niger to the Nile in the Oligocene, towards a situation whereby at Present day, the catchments of the two rivers and the sedimentation rates are seen to be similar. Explanations for the drainage change around the Eocene-Oligocene boundary include the the uplifts of the Darfur Swell, dated as late Eocene, and Afar Plume uplift. The initiation of these uplifts likely changed drainage patterns across Africa (Macgregor, 2010).

## Source-to-Sink Relationships

Given that we can now make some reasonable estimates for post-Eocene erosion over the key portions of the Nile catchment and have calculated a compacted sediment volume estimate for the Oligocene-Recent sediment of the Nile Delta/Cone, we are now able to investigate source to sink relationships. The best solution has been established that fits the erosion estimates and compacted sediment volumes (Figure 1), the elements of which are as follows:

- Over the Red Sea Hills, extending from the Gulf of Suez to Eritrea, we have established an average erosion of 1.5km, which when multiplied by the area of current Basement and Nubian Sandstone subcrop (Figure 1), gives an eroded volume of 2.17 x $10^5$ $km^3$; i.e., approx 38% of the sediment seen in the Nile Delta/Cone.
- Over the Ethiopian Highlands, independent calculations have been made by Pik et al. (2003), based on topographic reconstructions over the catchments of the main Blue Nile and Tekeze drainage systems, where average erosion is 860m and total eroded volume is 1.19 x $10^5$ $km^3$ or 21% of the sediment in the Nile Delta/Cone. Note 95 % of Present Day Nile sediment comes from this region, according to Shukri (1949).
- The Nile catches a huge area of Sudan and Nubia, of around 1.6 x $10^6$ $km^2$ (Figure 1), often eroding sand-prone material. Evidence described here suggests erosion is limited. However, the remaining 36% of Nile Delta/Cone sediment could be charged from this large region through an average erosion of only 130m, plus around 300m on the Nubian Sandstone subcrop area (Figure 1) and 200m on the Darfur Swell; all of these seem credible figures.
- Areas of Upper Cretaceous - Eocene limestone outcrop covering most of Egypt and the White Nile catchment, which is thought to have contributed only in the Pleistocene, are not assigned any contributing volumes. The limestone area could in fact be contributing small amounts of argillaceous material.

To constrain this rough source to sink relationship more accurately, further work would have to be conducted on Sudanese topography and the possible contributions to the Nile cone from Levantine rivers, amongst other things. However, this rough calculation shows that a long-term ‘Blue Nile’ model (i.e., encompassing all the tributary areas of that river and its continuation) is capable of supplying the sedimentary pile seen in the Nile Cone. The published palaeo-drainage models of Issawi and McCauley (1992) for the pre-Pliocene of Egypt, which drain sediment out of Egypt to the southwest and allow no Sudanese drainage connection to the Mediterranean, cannot, however, be supported by these figures. To fill the Nile Cone from Egyptian sediment sources alone would require erosion figures to be at least four times those estimated, e.g., 4.5 km of erosion on the Egyptian Red Sea Hills; this is inconsistent with the AFTA data or the typical heights of rift shoulders. The situation is exacerbated for the Miocene reconstructions of Issawi and McCauley, who have the Nile Cone catching only the northern portion of the Egyptian rift shoulders, requiring huge amounts of erosion in these small regions.

## Conclusions

Evidence from sedimentation rates and volumes in the Nile Delta and Cone, together with a synthesis of various onshore denudation studies, suggests the origin and outlet of the river have remained in much the same locations since the Oligocene initiation of the system, at least for the Blue Nile. During the early Oligocene, the rise of African swells led to a change in river patterns across Africa and caused systems which originally drained to the Niger to switch northwards to create the current Nile system (Figure 7), creating a major unconformity and facies change. Subsequent changes in the drainage system, based largely on the literature quoted, are highlighted in yellow on this figure.

The large sediment volumes measured in the Nile Delta and Cone are inconsistent with previously published histories of the river that do not include contributions from Sudanese and Ethiopian rift shoulders until relatively recent times. Most Nile sediment originates from the Red Sea rift shoulders during wet periods, with an additional contribution from erosion of sand-prone material over large areas of interior Sudan and Nubia. The White Nile is a recent addition, with little effect on sediment volumes.

Sedimentation rate changes and seismic facies indicators also suggest the prodelta sediment thick over the Oligo-Miocene section may have periodically switched between the Herodotus and Levantine Basins with distal turbidite reservoirs likely to extent well beyond Egyptian waters.

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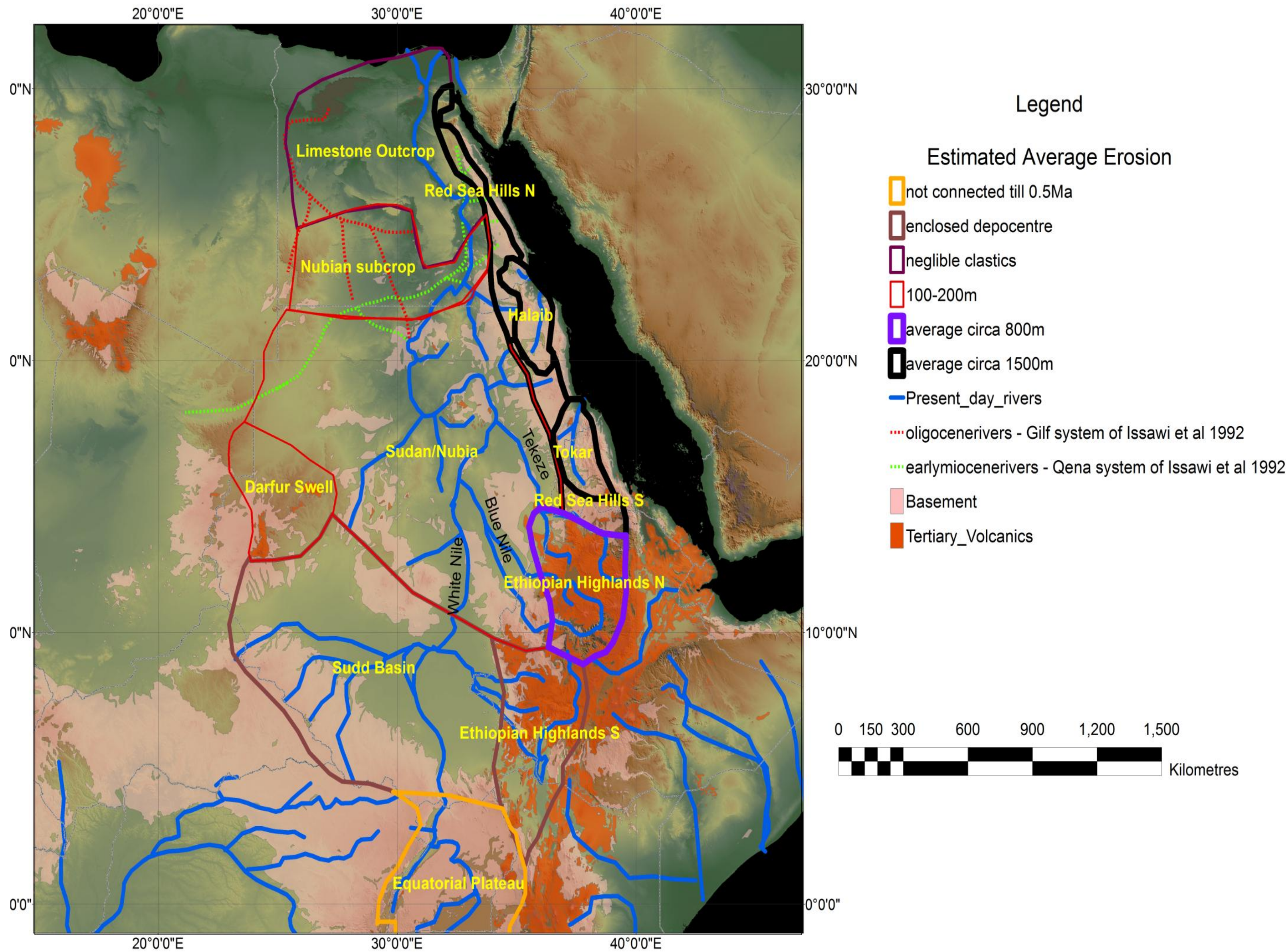


Figure 1. Present-day extent of the Nile catchment, divided into a number of segments for which an average erosion value is estimated (see later discussions) . Also shown are Issawi and McCauley (1992)'s reconstructions of Egyptian river systems in the Oligocene and Miocene.

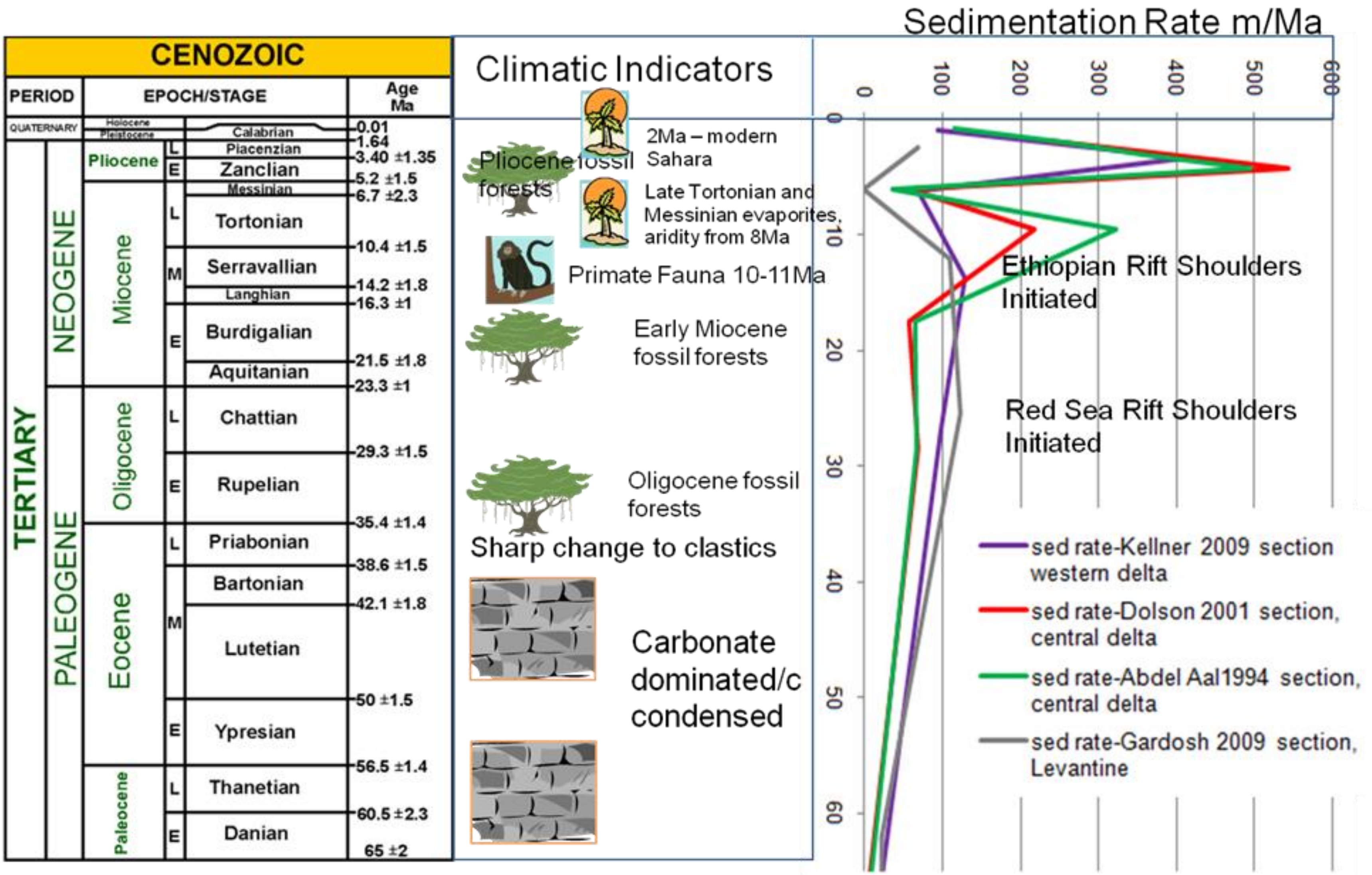


Figure 2. Palaeoclimatic evidence related to measured Nile Delta sedimentation rates, from published cross-sections.

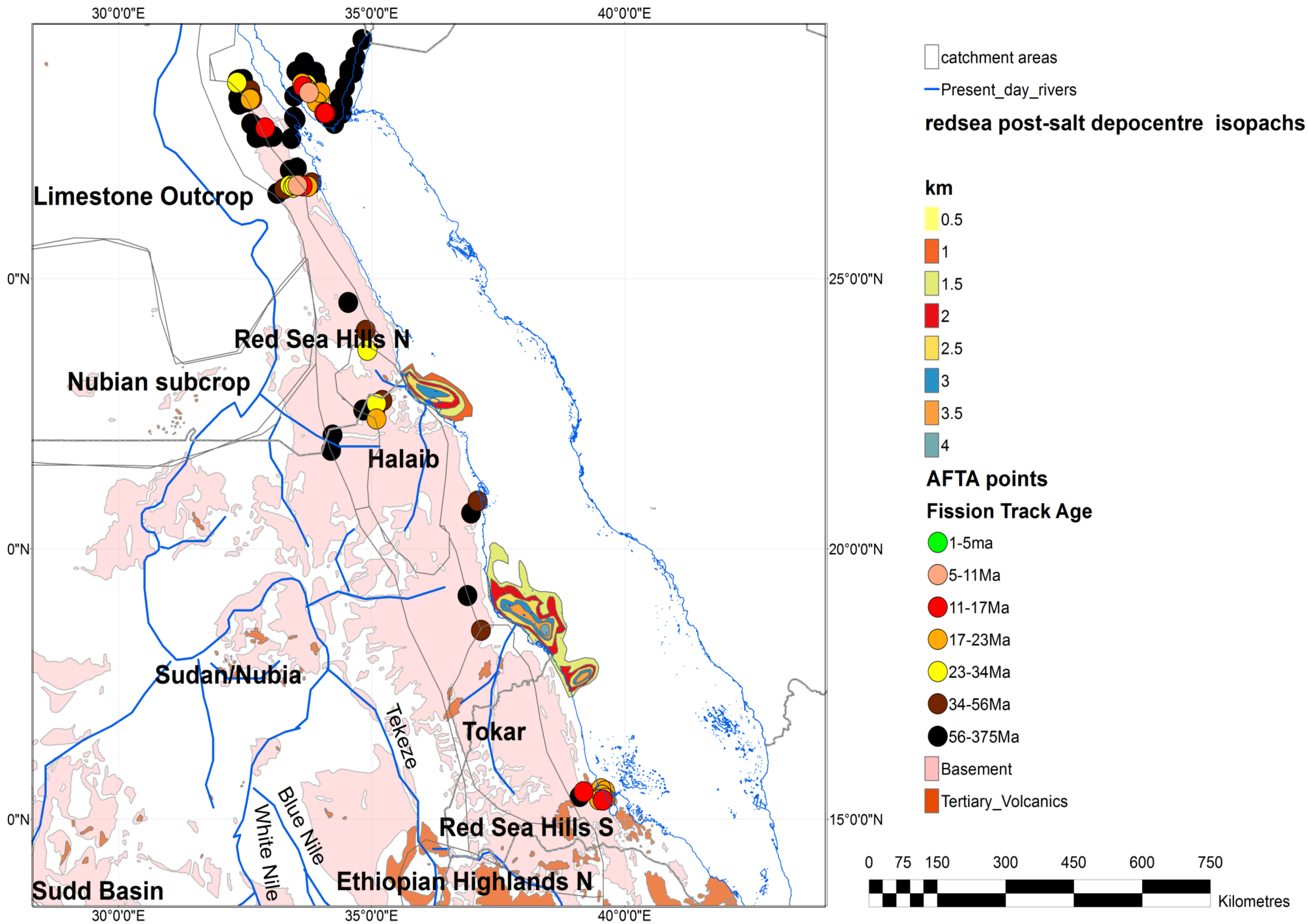


Figure 3. Apatite fission track ages over the Red Sea Hills. Also shown are the areas of the Halaib and Tokar catchments supplying the post-salt depocentres isopached offshore in the Red Sea.

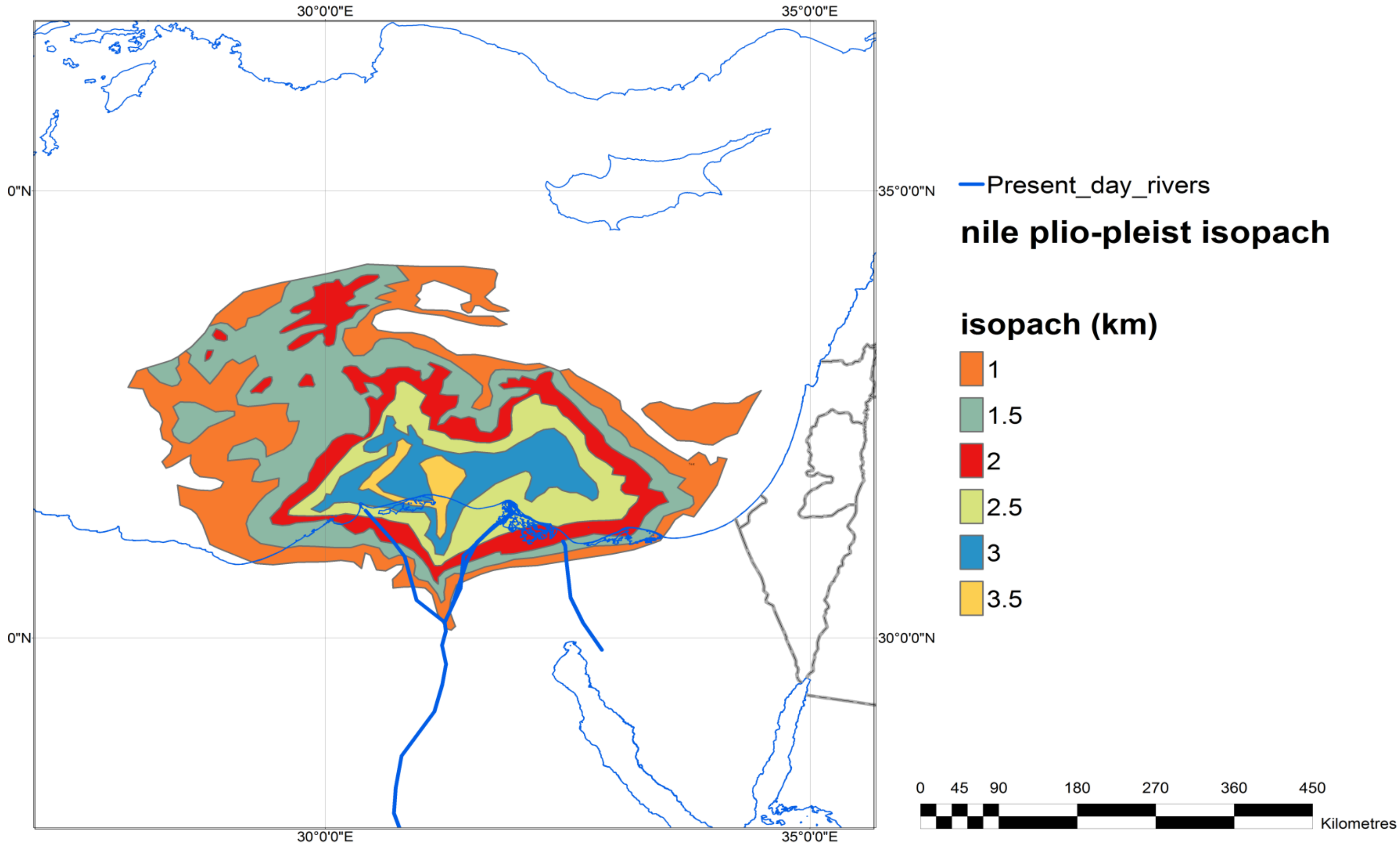


Figure 4. Plio-Pleistocene isopach of the Nile Cone (from Hall et al. , 2005).

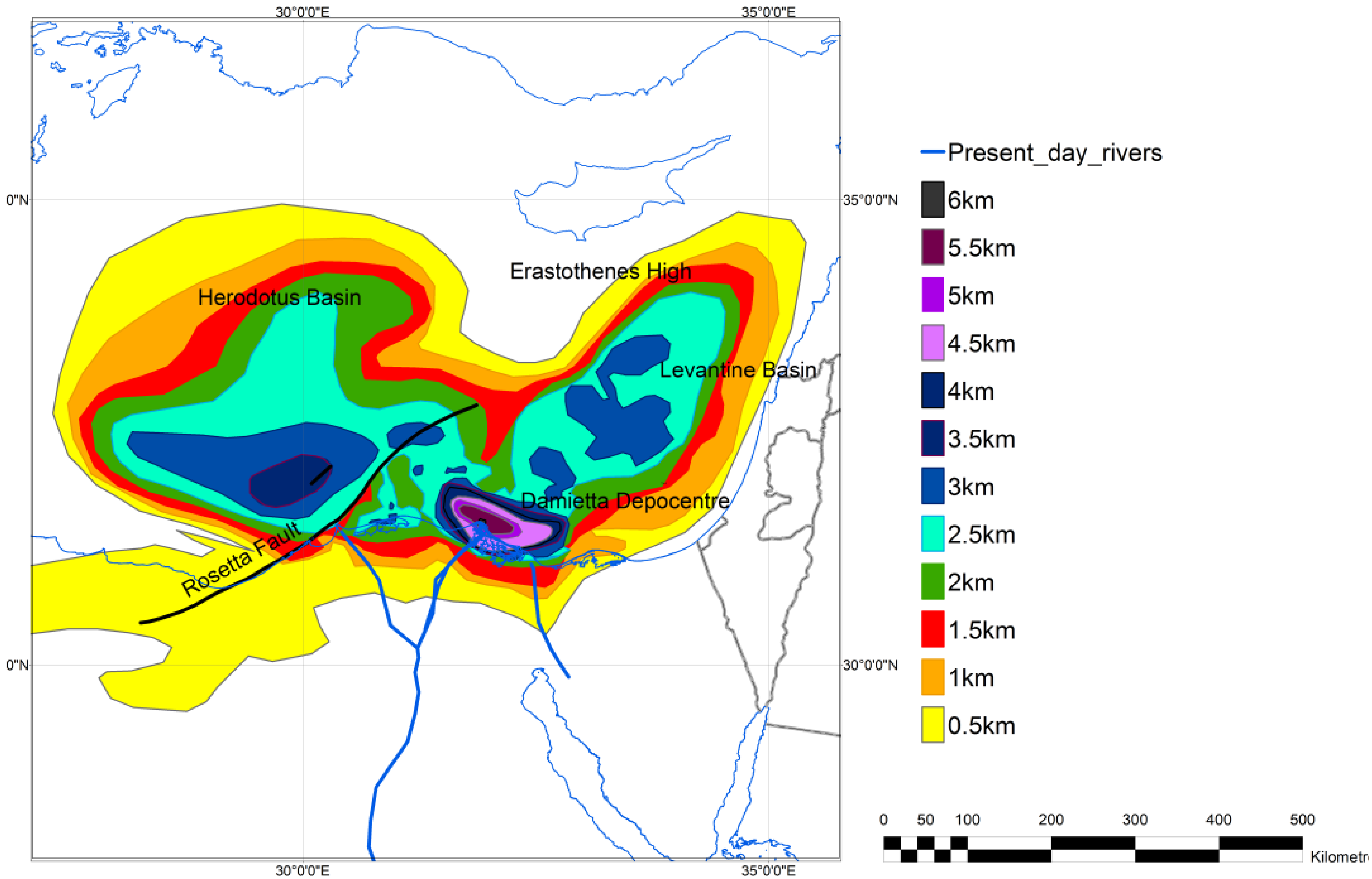


Figure 5. Oligo-Miocene isopach of the Nile Cone, Levantine and Herodotus basins.

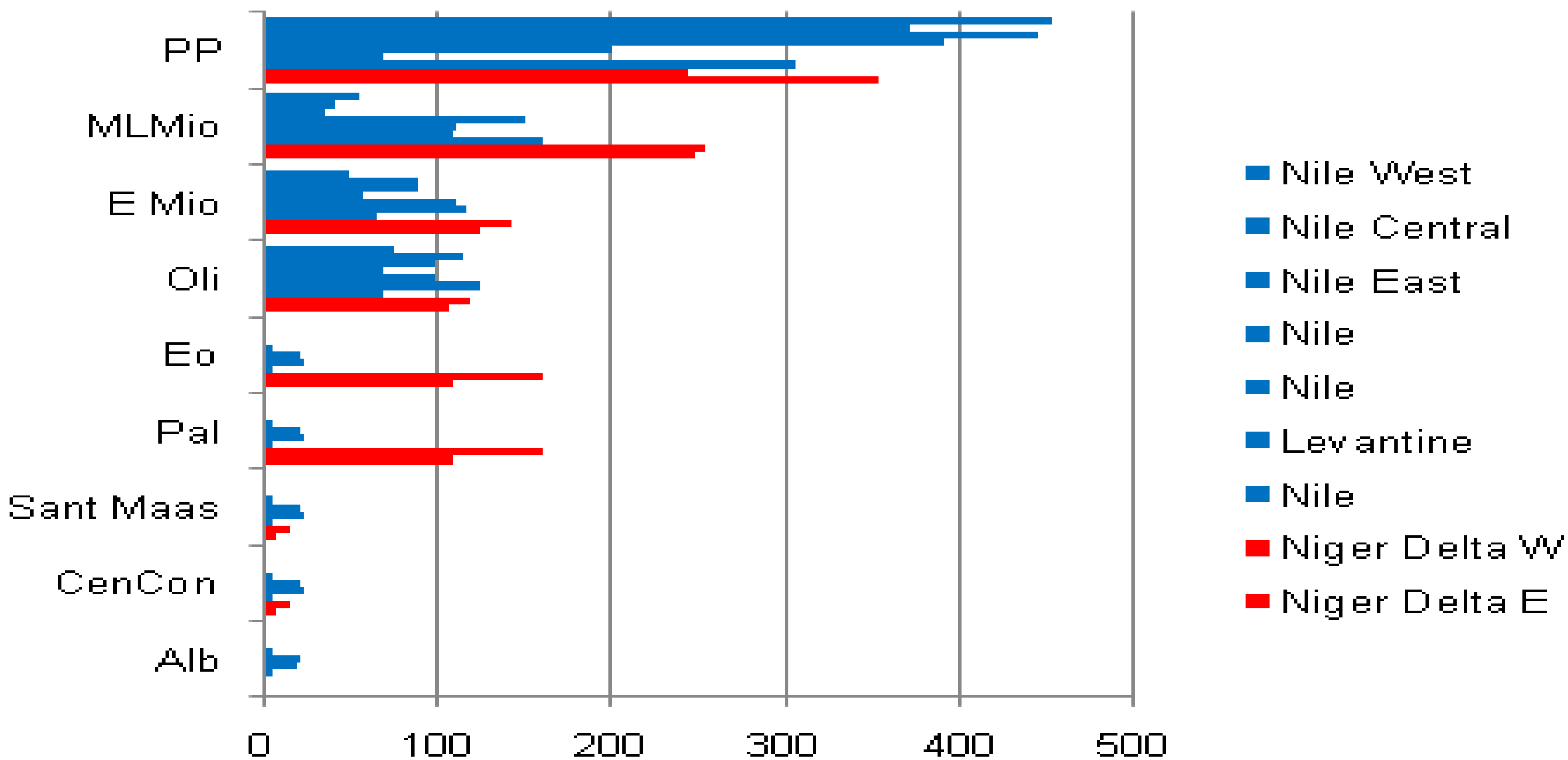


Figure 6. Compacted sedimentation rates for published cross-sections in the Nile and Niger deltas and cones.

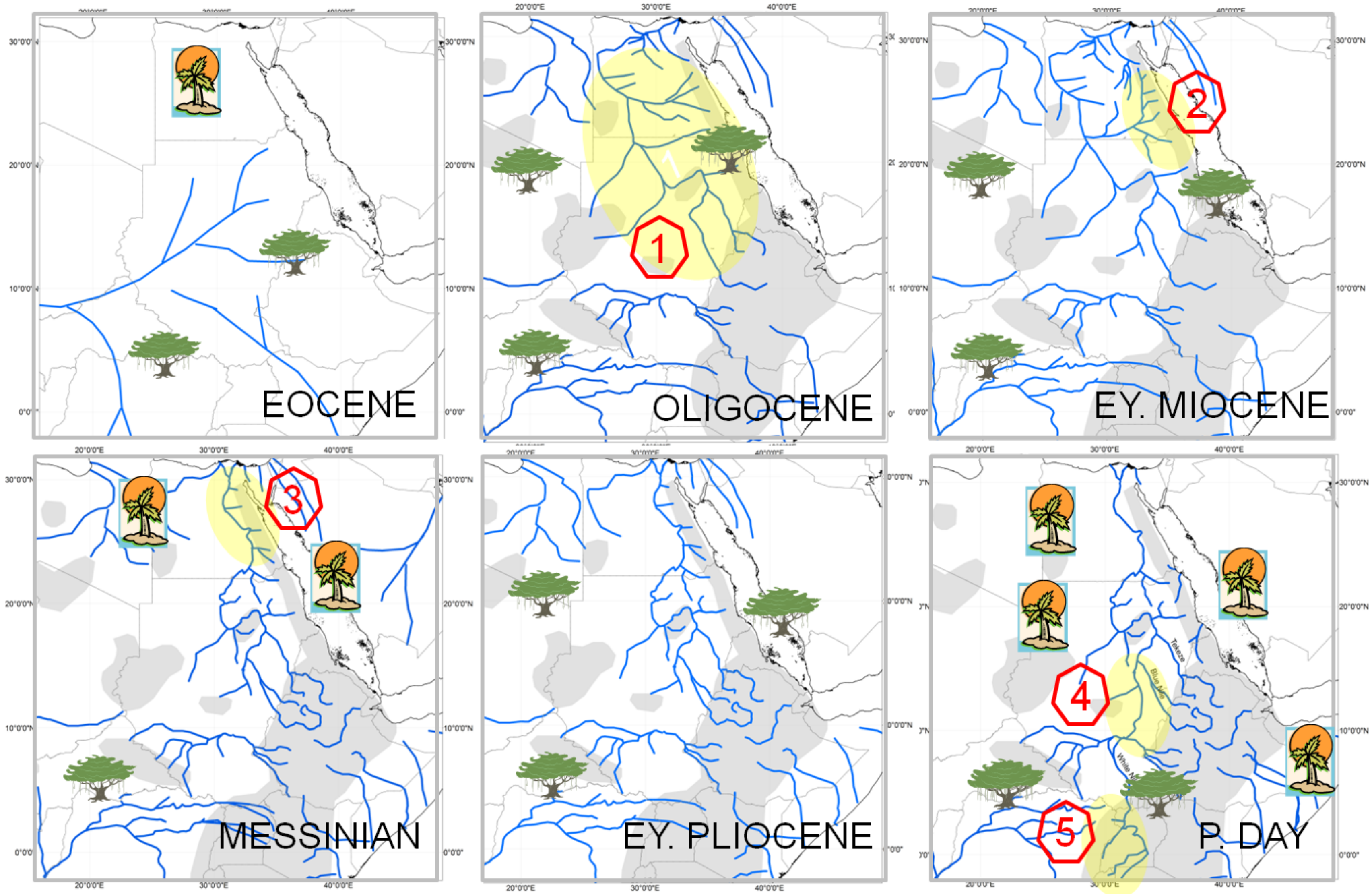


Figure 7. Interpreted history of the Nile drainage system, based on evidence presented in this article and the literature listed herein. Major changes include 1) Eo-Oligocene reorganisation of African river systems in response to swell uplift, 2) Switch from 'Gilf' to 'Qena' system in Egypt, though both drain to current river outlet, 3) Messinian downcutting creates 'Eo-Nile' of Said (1981), 4),5). Recent addition of White and Victoria Niles. Palm trees= arid conditions, Trees= seasonal or permanent forest (humid conditions). Swells and rift shoulders in grey.