The development of the Nile drainage system: integration of onshore and offshore evidence

Duncan S. Macgregor

Surestream Petroleum and MacGeology Ltd, Davidson House, 2 Forbury Square, Reading, UK
Corresponding author (e-mail: dmacgregor@surestream-petroleum.com)

ABSTRACT: This paper reconstructs drainage systems with outlets close to the present-day Nile system, honouring both onshore and offshore evidence and attempts a source to sink quantification. A large river is evidenced to have extended the length of the Red Sea Hills from Eritrea to the current outlet since the Oligocene. The early route of the river is uncertain through Sudan but a more westerly course is proposed through Egypt. The largest contributor of clastic sediment was the Red Sea Hills, where average erosion of the order of 1200–1500 m is constrained by a combination of Apatite Fission Track Analysis, planation surface analysis, and Red Sea sink volumes. Nubia was a significant supplier of sand-rich sediment during wet periods. This sediment supply pattern contrasts with the present-day situation where the Ethiopian Highlands contribute the vast majority of sediments, this contrast being validated by available mineralogical data. This is a consequence of wetter climates in the past and of the younger Ethiopian topography. The interpretations presented here illustrate the importance of hinterland climate change on clastic supply and allow the reservoir fairways in the Nile Cone to be more precisely mapped out in time and space.

INTRODUCTION

The Nile basin (Fig. 1) is one of the most pertinent regions with which to attempt a source to sink assessment. The study of source to sink relationships presented here, which it is hoped ultimately can be extended across Africa as published databases improve, benefits from a voluminous literature, from the availability of recently published offshore isopach maps, from moderately good controlling data onshore and from an appreciation of the principles of African geomorphology during the Cenozoic erosional cycle, as presented by King (1962) and Burke & Gunnell (2008).

Useful overviews on the principles of erosion and sediment supply are provided by Allen (1997), Hay (1998) and Hay *et al.* (2002). Analyses by these authors propose that the main controls on erosion rate are geology (which tends to be averaged over a wide region, thus diminishing its relative importance), relief (specifically the development and angle of slopes) and climate (maximum intensity of rainfall). Due to its varying topography and climate through time, the Nile represents an ideal laboratory to test these controls.

In this paper, the term ‘Nile’ is used loosely to refer to any river debouching close to the current river outlet during the Oligocene–Recent period.

PREVIOUS WORK ON THE NILE HINTERLAND

There is a considerable volume of literature debating the geological history of the River Nile, based on onshore geological and geomorphological evidence, with little calibration to offshore sedimentation. Previous interpretations fall into two schools. One school of workers (Butzer & Hansen 1968; De Heinzelin 1968; Wendorf & Schild 1976; Said 1981; Issawi & McCauley 1992) propose that an extended Nile did not connect from Ethiopia, Eritrea and Sudan through to the Mediterranean until at earliest Late Messinian times and, for some authors, not until the Holocene (e.g. Salama 1987, 1997). Evidence presented includes landform and radar analysis supporting a southwesterly flowing river in southern Egypt in Miocene times (that ultimately is proposed to feed the Niger), the apparent immaturity of the current Nile course through central Sudan, and mineralogical data indicating a diminishing contribution from Ethiopian volcanic sources with increased age. A second school of authors (Berry & Whiteman 1968; McDougall *et al.* 1975; Williams & Williams 1980; Burke & Wells 1989; Craig *et al.* 2011; Abdelkareem *et al.* 2012) favour a model by which a ‘Blue Nile’ and other Ethiopian tributaries originated in the Oligocene and follow varying courses through Sudan and Egypt to reach the current outlet, with Abdelkareem *et al.* (2012) suggesting an easterly course in Egypt during the Oligo-Miocene along the Qena valley and others a more westerly course. Evidence presented by the second school includes the large, though unquantified, sediment volumes in the Nile, which are proposed to be inconsistent with a purely Egyptian hinterland, and difficulties in taking a river westwards to Chad across the Uweinat-Darfur high trend. Both schools seem agreed that, on the basis of the presence of an endemic fauna with no Nilotic elements until *c.* 0.5 Ma in Lake Albert (Pickford & Senut 1994), and of the thickness of sediments in the enclosed Sudd basin of Sudan (Salama 1987), the White Nile (Fig. 1) is a recent river.

The present-day situation (Fig. 1) is summarized by Said (1981) and Woodward *et al.* (2007) who quote hydrological data showing that of water reaching Aswan prior to dam

Petroleum Geoscience, Vol. **18**, 2012, pp. 417–431
DOI: 10.1144/petgeo2011-074.

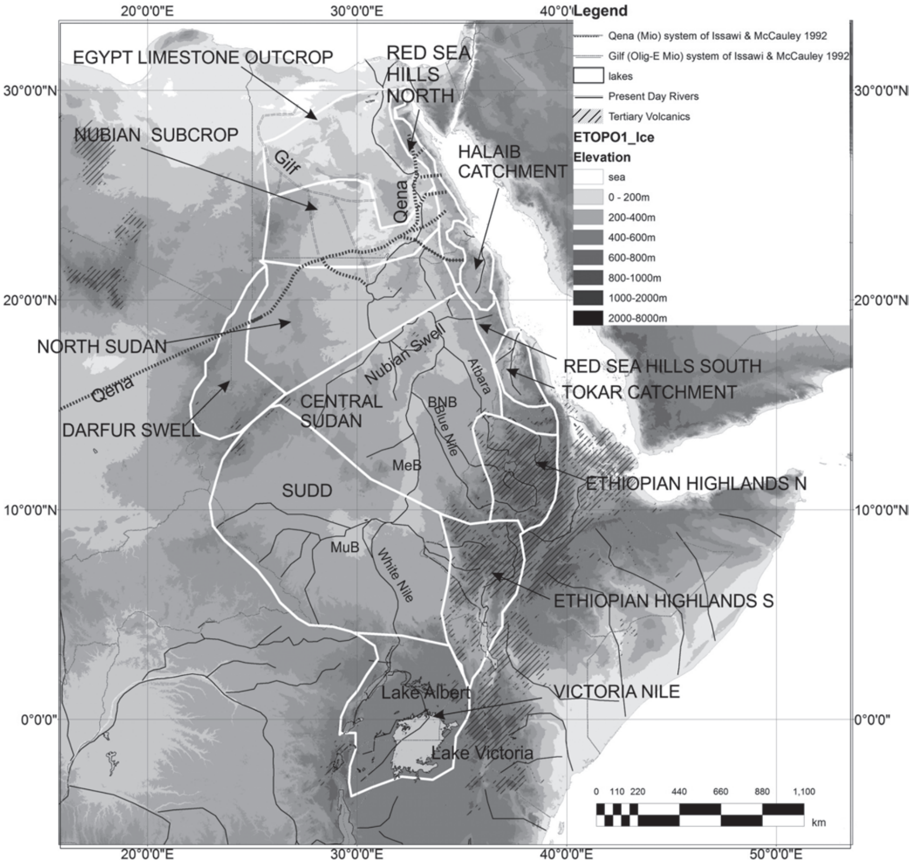


Fig. 1. Present-day extent of the Nile catchment, divided into a number of segments analysed in this paper. Also shown are Issawi's & McCauley's (1992)interpretation of Egyptian river systems in the Oligocene and Miocene. ETOP topography from Amante & Eakins (2009). Sudanese basins discussed in text: BNB, Blue Nile Basin; MeB, Melut (aka White Nile) Basin; MuB, Muglad (aka Bahr el Arab) Basin. Hatched area denotes the outcrop of Ethiopian trap basalts.

construction, about 70% originated from the Blue Nile and another major Ethiopian-sourced tributary, the Atbara, and 30% from the White Nile. Shukri (1949) and Woodward *et al*. (2007) measure the current relative suspended sediment load contributions as more extreme, with the Blue Nile and Atbara contributing over 95% of the 120 million tonnes of the load that reach Aswan.

Mineralogical data on older Nile Delta sediments are rather sparse but what published data exist indicate that the present-day sediment supply pattern described above is not representative of the past. The sediment supply from the Ethiopian Highlands is dominated by volcanic material, giving sediments rich in pyroxenes, which are preserved at present day as far as the current river mouth (Shukri 1949, 1953). Shukri shows the occurrence of augite (a pyroxene) to be lower in Plio-Pleistocene sediments than at present day, while analysis of a larger subsurface database by Zaghoul *et al*. (1980) shows that the Pliocene Kafr El Sheikh Formation contains more unstable minerals, including pyroxenes, than older sediments. El Sisi *et al*. (1996) analyse Serravalian–Tortonian reservoirs as having a mineralogy consistent with a Red Sea Hills source, while overlying Messinian reservoirs show evidence of an additional contribution from a distant plutonic source (perhaps in Sudan), with neither interval containing significant pyroxenes. The data as a whole, therefore, indicate diminishing Ethiopian relative contributions with increased age.

There is abundant palaeoclimatic data indicating that the Nile catchment periodically experienced much wetter conditions over most of the Oligocene to Pliocene period (Fig. 2), which would have increased the sediment flux from regions north of the Ethiopian volcanic outcrop. 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; Fig. 2); the Tortonian, when a wide-ranging mammalian fauna is known to have occurred in the Western Desert (Pickford *et al*. 2006); the Early Miocene and parts of the Oligocene, both represented by the abundance of fossil wood in Western Desert strata (Said 1981). These periods do, however, seem to have oscillated, often rapidly (e.g. Griffin 2002) with periods of drier and possibly Sahara like conditions, when ferricrete soils were developed in Sudan (Schwarz & Germann 1999) 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 occurring of granitic material on the Red Sea rift shoulders and of the subcropping 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 further north, and were later reworked into deep water during lowstands.

All authors agree that the segments of Red Sea Hills considered in their relative catchments are a major source of Nile sediment (e.g. Burke & Wells 1989). These represent the only significant area of the catchment north of Ethiopia where there has been both major uplift and deep erosion into basement. The structural history of this key region is summarized by Bosworth *et al*. (2005), who interpret that uplift of the rift shoulders commenced around 24 Ma and peaked around 20 Ma, though Omar & Steckler (1995) interpret an earlier pulse at ~34 Ma. The occurrence of Late Oligocene gravels overlying the Egyptian limestone plateau (Said 1981; Issawi & McCauley 1992) are consistent with an Oligocene date for the initiation of Red Sea uplift, as are the profiles presented on Figure 2. The Ethiopian Highlands are generally considered to be much younger, although

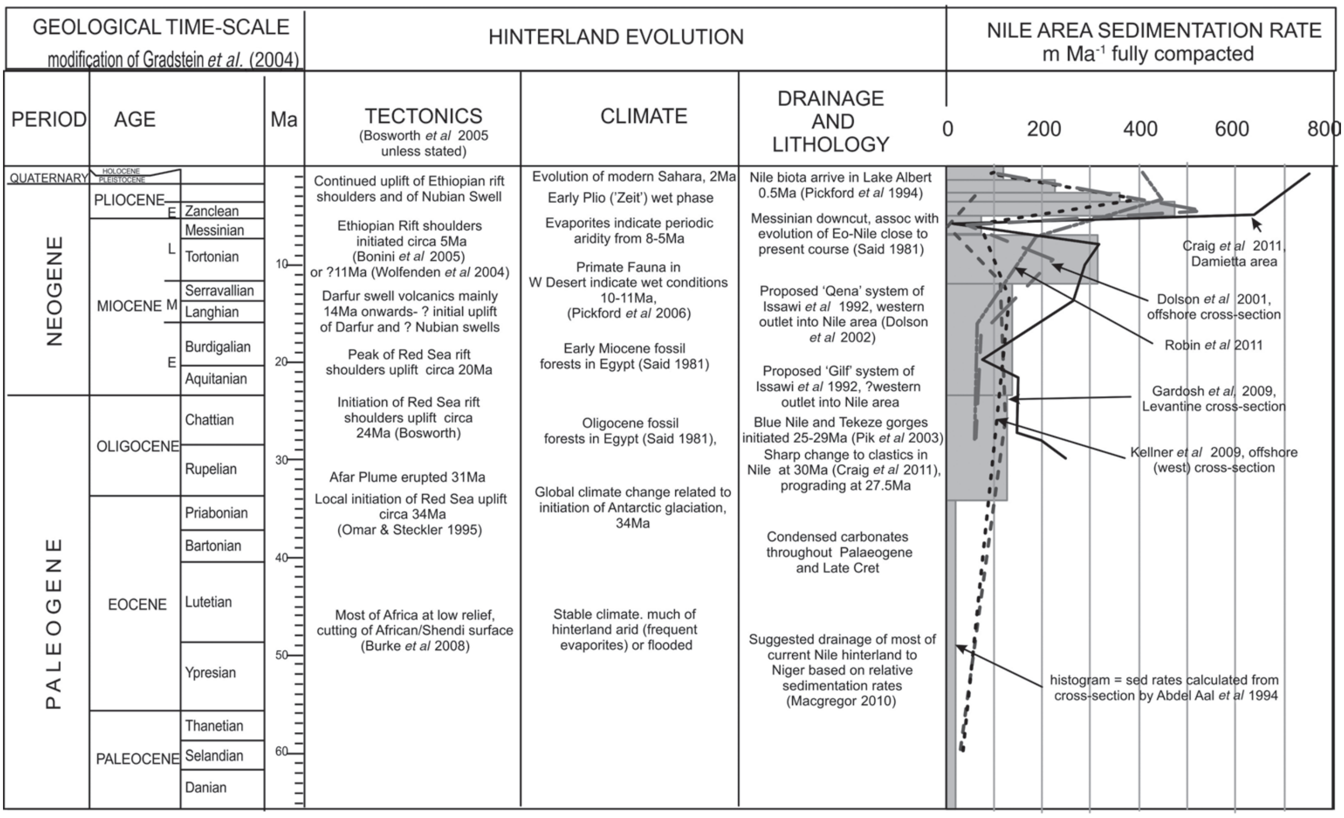


Fig. 2. A summary of key events in the Nile catchment area through the Cenozoic. Note the concentration of events in the Oligocene that lie close to the interpreted onset of the system at 30 Ma. The Pliocene sediment surge could be attributed to rapidly oscillating climates or to the uplift and connection of Ethiopia. Sedimentation rate plots calculated from cross-sections in the references quoted. That calculated from an offshore cross-section of Abdel Aal *et al*. (2001) is shown as a histogram, while others are plotted on the mid-points of the time ranges assessed.

gentler relief of *c*. 1 km may have been established by the Afar Plume at *c*. 31 Ma (Sengor 2001). The initial uplift of the Ethiopian rift shoulder, which led to the development both of a high topography and related wet climate, is dated by Wolfenden *et al*. (2004) as 11 Ma based on Ar/Ar dating, although comparisons with the Kenya rift shoulder, where more precise stratigraphic control is available, accompanied by some more recent volcanic dating, suggests an initiation at *c*. 5 Ma (Bonini *et al*. 2005). Gani *et al*. (2007) believe the Ethiopian plateau may have risen over 1 km in the Early Pliocene, which would coincide with a sediment surge at this time (Fig. 2).

Egyptian outcrop geology and landforms are well documented and are suggestive of a differing course of rivers prior to the Messinian. Issawi & McCauley (1992) interpret two major systems: (1) the Oligocene–Early Miocene 'Gilf' system (Fig. 1), which drained from the Egyptian Red Sea rift shoulders towards the Western Desert, probably turning north to probably join an incised valley system and outlet documented by Dolson *et al*. (2002); and (2) the Early to Mid-Miocene 'Qena' system, which drained most Egyptian rivers of that age southwestwards into Nubia and, thereafter, under their model, into Chad and the Niger drainage system (Fig. 1). However, a major river may still have existed in the Western Desert, where Brooks (2001) documents major Mid-Miocene flood episodes. The Plio-Pleistocene history of the Nile and its precursors is well documented in the seminal publication of Said (1981) and his conclusions over that interval will not be challenged here. Investigations of palaeo-river courses further south are few, though Pik *et al*. (2003) propose that the Blue Nile and Tekeze (headwater of Atbara) canyons began to be cut at 25–29 Ma on the basis of apatite helium dating.

Attempts will be made in this paper to honour all the previously gathered onshore evidence presented above, as condensed in Figure 2, into an integrated model. For the first time, it is now possible to properly integrate offshore data, particularly the calculation of sink volumes and, despite considerable statistical uncertainty, this is shown to constrain the models presented for the past development of the Nile catchment.

EROSIONAL AND SOURCE VOLUME ANALYSIS: TECHNIQUES AND UNCERTAINTIES

Quantification of source and sink volumes are uncertain calculations with wide error bars. In this paper, a variety of techniques are used to determine source volumes in different parts of the Nile catchment, while the calculation of sink volumes is based primarily on isopach mapping, but with an attempted calibration to adjoining sinks. Wherever possible, multiple techniques are used to constrain the range of estimates.

Apatite Fission Track and related analyses

A quantification of erosion can be interpreted from Apatite Fission Track Analysis (AFTA) studies. The main measurement taken is the 'fission track age', representing the most recent period of cooling through *c*. 110°C, a temperature at which tracks start to be developed, the age being then estimated by the density of tracks since formed. Rapid cooling, it is assumed, is primarily related to removal of an overburden by erosion. For an individual outcrop sample, from an assessment of geothermal gradient, it is inferred that sample has experienced diminishing temperature from 110°C to surface temperature over the period from the fission track age to present day. Using an assumed geothermal gradient, it is then possible to interpret an eroded thickness and erosion rate over that period. A similar technique, based on apatite helium thermochronometry, can be used for temperature regimes of *c*. 80–90°C (Pik *et al*. 2003). No interrogation or re-analyses of these data and interpretations is attempted in this paper, though a number of uncertainties are recognized: (1) ages are based on track counting, with accuracy dependent on sample choice and preparation; (2) there is considerable uncertainty about past geothermal gradients, while surface temperatures may also have varied with palaeoclimate and elevation and thus affected the calculation of erosion; and (3) the AFTA sample points are representative of regional erosion, with a dependency on current elevation often apparent. Samples tend to be taken in valleys, resulting in averaged regional erosion being overestimated.

Planation surface analysis

King (1962) and Burke & Gunnell (2008) describe the erosional pattern of Africa during the Cenozoic erosional cycle, typified by the retreat of escarpments capped by uplifted pediplanation surfaces. These surfaces, including the particularly well-developed ‘African’ surface, were formed during periods when Africa was a low humid flat-lying continent and their current elevation is due to subsequent regional uplift. The African surface is thought to have been cut in the early Paleogene, was uplifted in north and east Africa from the Oligocene onwards (Burke & Gunnell 2008), and has since been deeply eroded to provide the sediments seen in African margin basins, such as the Nile. The surface is often seen as an ironstone, bauxitic or lateritic surface. Nile sediments are superimposed on the supposed Sudan equivalent, the ‘Shendi’ surface (Berry & Whiteman 1968). Assessments of eroded thicknesses or volumes are, therefore, possible by subtracting the present-day erosional topography from an extrapolation of these planation surfaces into the air, based on their elevation and dip on hilltops on which they are preserved. However, as in other parts of Africa, there are likely to be surfaces younger than the Paleogene ‘African’ surface, which may itself be heavily diachronous.

Uncertainties in such calculations essentially are related to the correct identification, dating and extrapolation of the surfaces. In many cases, the surface considered may not have been as flat as assumed. In addition, the present-day topography in low areas may contain substantial thicknesses of drift over bedrock. These drift volumes should strictly be removed and included in sink volumes, though their net effect when attempting a source to sink balance is small as they are not included in either side of the calculations.

Back-calculation from offshore sink volumes

Estimates of average erosion for the catchment of a drainage system can be made by calculating the compacted sediment volume in the associated sink (through methodologies described later in this paper) and dividing that by the catchment area. In addition to the uncertainties described below for calculating sink volumes, a key assumption is that present-day catchment areas also represent past catchments.

EROSIONAL AND SOURCE VOLUME ANALYSIS: CALCULATIONS (TABLE 1)

For the purpose of making sink volume estimates, the present-day catchment area of the Nile has been subdivided into a number of segments (Figs 1, 3), with an average erosion estimated for each over the Oligocene–Recent interval, which is then multiplied by the area of that segment to give a source volume. Segments are discussed below in order of decreasing distance from the Nile outlet and, consequently, increased uncertainty that they made a significant contribution to Nile Cone sediment volumes.

Egypt Limestone Plateau and surrounding area

Over southern Egypt, erosion of Eocene and Late Cretaceous limestones is slowly continuing by scarp retreat. Control points on which to estimate this erosion for the Oligocene–Recent period are provided by the elevation of the Eocene–Oligocene contact, which is marked by a sharp facies change from carbonates to clastics (Dolson *et al*. 2002). This outcrops in northern Egypt (Fig. 3) and is locally preserved on the limestone plateau, where Oligocene gravels overlie Eocene limestones (Said 1981), which lie at current elevations of up to 600 m. In comparison, in the Nile valley, Butzer & Hansen (1968) describe the highest pediment around the Nile valley at 360 m and suggest a Paleogene age for this. From these data (Fig. 3), the Eocene–Oligocene boundary is extrapolated at over 500 m average elevation and average erosion is calculated at 218 m. Erosion in this area is purely of carbonates, with clasts of these seen in Nile sediments (El Sisi *et al*. 1996), indicating detrital erosion and transport to the sink as well as in solution.

Egyptian Nubian subcrop

Average erosion over the outcrop of the Nubian Sandstone seems to be around 150 m (Table 1) according to extrapolation on cross-sections from hydrogeological studies (e.g. Gossel *et al*. 2004) and the current elevation of laterite surfaces (Fig. 3, see Sudan section below for discussion of these). This eroded material will have been very sand prone.

Red Sea Hills (north and south segments)

The current Red Sea Hill catchment of the Nile is divided into two segments to allow interrogation of different models for past Nile catchments later in this paper. Erosion estimates are possible on a variety of techniques, but each carries uncertainties and wide ranges result. This is partly because uplift has clearly been variable, increasing towards the Red Sea rift shoulder and it is difficult to make judgements on average rather than maximum erosion, which undoubtedly is in excess of 2000 m.

The basement of the Red Sea hills has been heavily analysed with AFTA. Of some 111 points measured between Sinai and Eritrea (Kohn & Eyal 1981; Ghereab *et al*. 2002; Omar & Steckler 1995; Fig. 4), 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, indicating a level of erosion not evidenced for any other part of the continent for this time, including areas of similarly long-lived topography, such as the South African plateau and the Ahaggar Massif (Burke & Gunnell 2008; Macgregor 2010). Application of current average geothermal gradients in the Red Sea (*c*. 40°C km^{-1}) would imply that *c*. 2000 m of overburden has been removed since the fission track age of each sample. Since about a third of the samples suggest that a 2000 m or greater overburden existed at Oligocene time, while the other two-thirds suggest a lesser overburden than this, then average erosion of around 1500 m for the sample set seems a reasonable estimate. This is corrected to 1300 m as the average altitude of the samples is 200 m below the average current altitude of the region. It is possible, by comparison with other rifts (e.g. the Rhine Graben), that geothermal gradients on the rift flanks may be lower than in the rift itself, and the application of a lower geothermal gradient would lead to an increase in eroded thicknesses. The application of a global average geothermal gradient (probably an extreme case) would lead to an upside figure of around 1900 m for average erosion.

Table 1. *Compendium of source volume calculations*

Initial erosion calculations							Input sediment volumes to modelled cases						
Nile drainage sector	Area (km^2)	Est. average 30–0 Ma erosion (m)	Methods used	Volume eroded (km^3)	Sediment yield km^3 Ma^{-1} (30–0 Ma)	Av. erosion rate m Ma^{-1} (30–0 Ma)	Issawi & McCauley case (km^3)	Case 1 volume delivered to sink (km^3)	Case 2 volume delivered to sink (km^3)	Case 3 volume delivered to sink (km^3)	Case 4 volume delivered to sink (km^3)	Case 4 percentage contributions to Nile sink	Changes to initial erosion and sediment volume calculations for cases considered
Limestone outcrop	321 325	218	planation analysis	70 049	2.3	7.3	70 049	70 049	70 049	70 049	70 049	12	Predominantly carbonate
Nubian subcrop	287 998	150	planation analysis and cross-sections	43 200	1.4	5.0	43 200	43 200	43 200	43 200	43 200	7	
Red Sea Hills N	70 091	1200	AFTA, planation analysis, calibration to adjoining sinks	84 109	2.8	40.0	84 109	84 109	105 136	105 136	105 136	18	I&M case assumes supply in Pli-Pleis. only, with 33% of total sed. volume. Cases 2–4 assume 25% increase in erosion (average 1500 m)
Red Sea Hills S	74 742	1200	as above	89 690	3.0	40.0	29 598	89 690	112 113	112 113	112 113	19	as above
Tokar	63 582	1800	as above	114 448	3.8	60.0	0	0	102 191*	102 191*	38 692*	7	Cases 2 and 3 are upsides that include all eroded products except volumes seen in Red Sea post-10 Ma. Case 4 is a reasonable most likely for a pre-Pliocene contribution.
Halaib	59 565	1200	as above	71 478	2.4	40.0	0	0					
North Sudan	471 128	95	planation analysis	44 757	1.5	3.2	14 770	44 757	44 757	44 757	44 757	8	I&M case assumes supply in Pli-Pleis. only, with 33% of total sed. volume
Central Sudan	769 750	85	as above	65 429	2.2	2.8	21 591	65 429	65 429	65 429	65 429	11	as above
Darfur Swell	186 881	100	as above	18 688	0.6	3.3	61 67	18 688	18 688	18 688	18 688	3	as above
Ethiopian Highlands N	140 000	850	planation analysis of Pik *et al.* (2003) and McDougall *et al.* (1975)	119 000	4.0	28.3	0	0	0	119 000	83 300	14	Case 4 assumes sediment supply in Plio-Pleist only, assumed to be 70% of total eroded
Totals	2 123 737		incl. carbonate	**680 562**			**269 484**	**415 992**	**561 562**	**680 562**	**581 363**		
			excl. carbonate	**610 513**			**199 435**	**345 943**	**491 513**	**610 513**	**511 314**		

The left-hand columns present an estimation of average erosion made over each segment by techniques discussed in the text, which is multiplied by the segment area to give an initial assessment of volume eroded for the Oligocene (30 Ma)–Recent period. The right-hand columns present various manipulations and combinations of these data to construct the total source volume cases presented in Figure 9. The downside Red Sea Hills erosion case is presented in the left-hand column and included in Case 2, while the upside case is applied to Cases 3–4. Further explanation of the cases considered is summarized in the right-hand column.

*Tokar and Halaib volumes combined

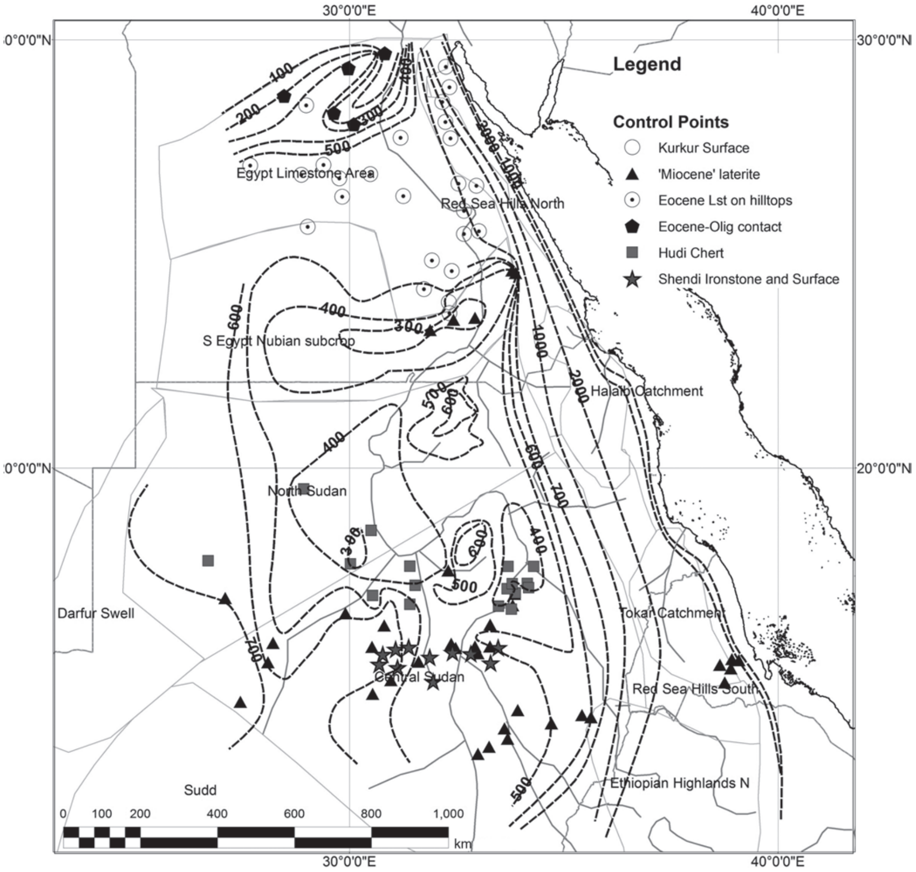


Fig. 3. An interpretation of present-day altitude of the 'Shendi surface' (Berry & Whiteman 1968), and possible equivalents, including the lateritic surfaces of Schwarz & Germann (1999), the Eocene–Oligocene facies change, the probable Oligocene Hudi Chert (occurrences from Whiteman 1971) and the highest river terraces in the Nile area. Maximum elevations of Eocene strata are also included. The extrapolated surface is thought to represent an uplifted originally near-to-flat surface and is compared with the current DEM to calculate erosion. Contours in metres.

Study of digital elevation model (DEM) images shows the Red Sea Hills to be highly dissected, devoid of any preserved area of remaining plateau, other than in Eritrea, where elevations reach 3000 m, though the plateau there is at a more typical elevation of 2000–2500 m. Eocene strata also reach elevations in excess of 1300 m on the flanks of the Gulf of Suez (Fig. 3). This eroded framework is clearly not consistent with the current climate and also appears more advanced than the conjugate Saudi Arabian–Yemeni rift shoulders. Lateritic surfaces are described from the Eritrean plateau (Schwarz & Germann 1999), which are interpreted as preservation of an originally flat-lying surface that was cut prior to uplift. These authors describe them as 'Miocene', though there is no dating in this area: if this was the case then Oligocene erosion would not be considered by this method and the erosion values would be underestimates. This enables a crude extrapolation of an uplifted surface (Fig. 3), which when related to present-day topography, results in a calculation of average erosion of about 900 m in the segments currently draining to the Nile and 1100 m for those draining to the Red Sea.

Another estimate of erosion over portions of the Red Sea Hills can be obtained through comparing sink volumes in depocentres offshore Red Sea with the current areas of their drainage catchments (Table 2). This has been attempted here for the Halaib and Tokar depocentres, using a post-evaporite isopach map of Mitchell *et al*. (1992; Fig. 4) and methodologies for sink volume calculation described later in this paper. According to the stratigraphy of Bosworth *et al*. (2005), the post-evaporite sequence covers the period of 10 Ma–Recent. Dividing the calculated compacted sediment volume by the areas of the present-day catchments gives average erosion values of 400 and 900 m for the two catchments over that period (Table 2). Since the period of 0–10 Ma covers about a third of the erosional period of the rift shoulders, and about half the sediment volume seen in the Nile Cone (see sink volume estimates following and profile on Fig. 2), these figures can be roughly doubled (Table 1) to give estimates of post-Eocene erosion, which would then suggest an average of around 1300 m average erosion for these segments. However, as suggested below, the drainage area of the Tokar and Halaib into the Red Sea may have increased with time, which – if correct – would imply a lower catchment area for part of the period considered and imply that this erosion figure may be an underestimate.

There is also a strong possibility that the catchment area of the Nile and its precursors from the Red Sea Hills has changed with time. Currently, about half the total area of the Red Sea Hills drains to the Red Sea, most of this within the Tokar and Halaib catchments. Study of less mature (Pliocene) rift shoulders, e.g. Ethiopia and Lake Tanganyika, suggests that an earlier drainage could have predominantly followed the slope of the rift shoulders and thus supplied more Oligocene–Miocene catchment and sediment to the Nile. Under such a model, Red Sea rivers would have later cut progressively back into the rift scarp to capture the rivers flowing down the rift shoulder slope. Isopach maps of Oligocene and Miocene sediments of the Red Sea are not available to support this model but it is notable that Bunter & Abdel Magib (1989, figs 4, 11) indicate a pre-evaporite (>10 Ma) Oligo-Miocene clastic section generally under 1 km thick in the Sudanese Red Sea, as compared to over 4 km of post-10 Ma sediment .

Due to these uncertainties, it is not appropriate to produce a single erosion estimate for the Red Sea Hills and two scenarios are considered in Table 1, which give a range to be considered when making the eventual source to sink balance for the entire Nile catchment. After compensation for altitude differences, estimated average erosion over the Red Sea Hills calculated by the different methods ranges from 1000 to 2000 m, but with an overlap between

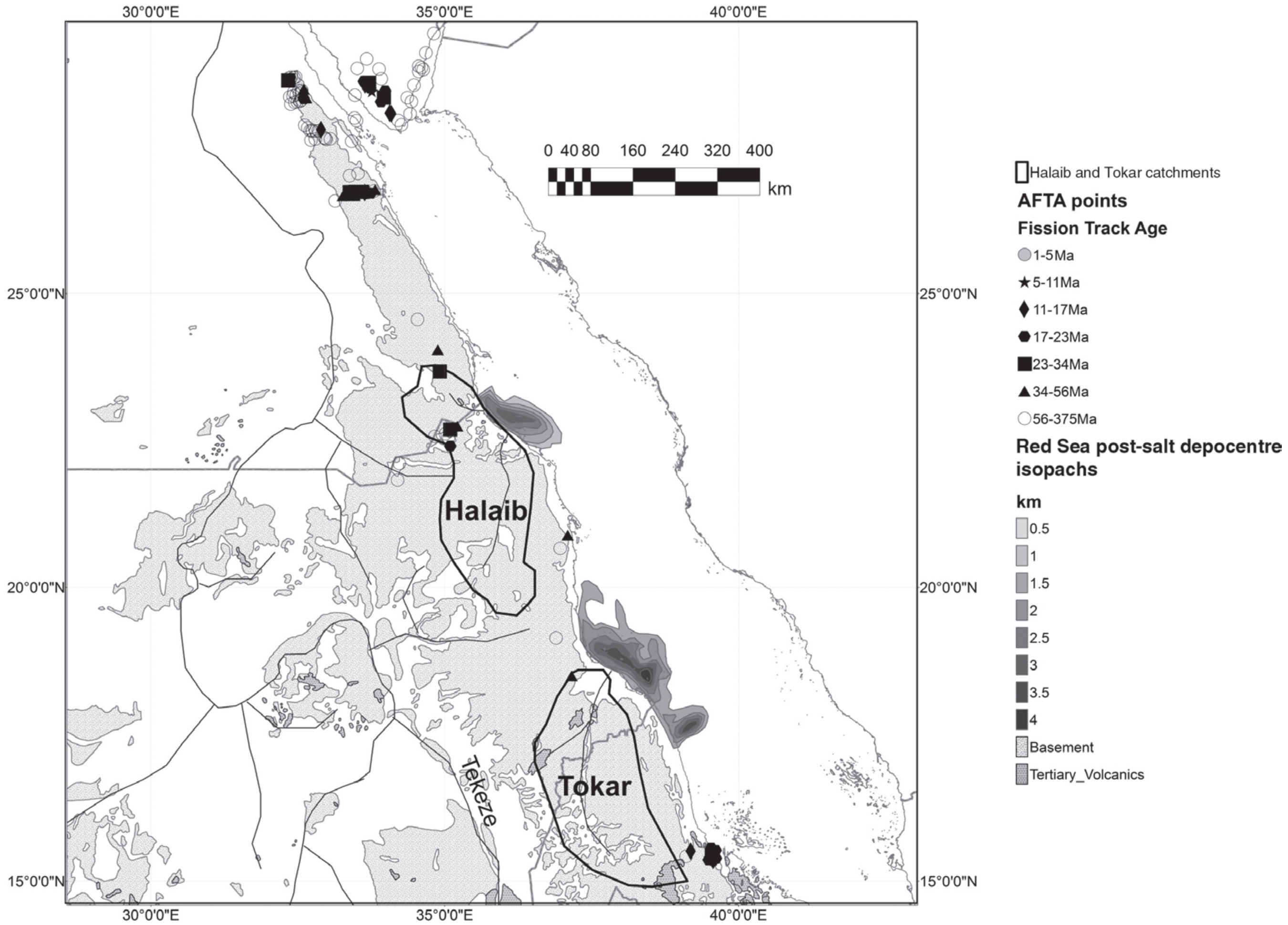


Fig. 4. Apatite fission track ages over the Red Sea Hills. Also shown are the areas of the Halaib and Tokar catchments supplying the post-salt depocentres isopached offshore in the Red Sea. These data form the basis of the eroded volumes estimated, which indicate this region to supply about half of Nile clastic sediment.

the methods of most likely values around 1100–1300 m. A downside eroded volume calculation thus assumes an average of 1200 m erosion over the Red Sea north and south segments, while an upside calculation increases this to 1500 m, taking account of various possibilities described by which the methodologies may be underestimating erosion. The upside calculation also includes the Tokar and Halaib catchment area volumes, minus the sediment volume derived from these segments measured in the 10–0 Ma section in the Red Sea. This would thus be roughly equivalent to a case where drainage switched at around 10 Ma at the end of Red Sea salt deposition. In all likelihood, it was more gradual than this, and there were still some pre-10 Ma rivers draining to the Red Sea, so this is an extreme case.

Sudan

Excluding the Sudd Basin, to be considered later, Sudan is considered in two segments, north and central, so that an area in the north of a wide apparently mature river valley can be separately considered from that of an apparently less mature topography in the Nubian Swell and Khartoum regions.

Over much of Sudan, hilltops are capped by the 'Shendi' lateritic or ironstone surface (Berry & Whiteman 1968; Whiteman 1971; Geological Research Authority of the Sudan/Robertson Research 1988; Fig. 3), which is believed by these authors to be an uplifted erosion surface of pre-Oligocene age and the equivalent of King's (1962) African surface. Schwarz and Germann (1999), however, include the Shendi laterites in a compilation map of 'Miocene' laterites, although the only dating they quote is a single sample of Oligocene age. Further control points are provided by the sparse occurrences of the 'Hudi Chert', as reported in Whiteman (1971), which he assigns uncertainly to the Oligocene. Dating and correlation of this combined surface is thus an issue, though the altitudes from the different categories are consistent between nearby data points and it is possible to combine them into a credible altitude map. The surface obtained is extrapolated into the air (Fig. 3) and the present-day DEM is subtracted from it. This indicates average erosion over both segments of just under 100 m (Table 2), a low figure which is consistent with the very low gradient of the river at present day. It is also notable from Figure 3 that the folding of the planation surface mimics present-day topography, though at lower relief, supporting the notion that the north–south trends of a depression through Sudan and of a high to the west dates backs to the Oligocene, thus making it difficult to take Issawi & McCauley's (1992) 'Qena' drainage system across these old trends.

It follows from this that it was the initial folding of the Shendi surface that first led to the formation of a south–north drainage system across Sudan. The current course of the Nile through the Central Sudan segment, particularly the Great Bend cataract area, is clearly an immature one and an alternative path must be sought. This is a consequence of relatively young uplift of the Nubian Swell (Thurmond *et al.* 2004), which has clearly diverted the

Table 2. *Compendium of sink volume calculations*

Basin	Age	Period (Ma)	Isopach cut-off (m)	Area (km^2)	Av. sed. thickness − current compaction (m)	Av. sed. thickness − fully compacted (m)	Sink volume uncompacted (km^3)	Sink volume − compacted (km^3)	% of total	Source area (km^2)	Implied av. erosion	Implied av. erosion rate (m Ma^{-1})
Nile	Plio-Pleistocene	5.3	1000	14 6951	2010	1280	295 372	188 097	32	2 123 737	89	16.7
Nile	Oligo (30 Ma)–Miocene	24.7	500	20 7857	2275	1892	472 875	393 265	68	2 123 737	185	7.5
Nile	Total period (30–0 Ma)	30			4285	3172	768 246	**581 363**			274	9.1
Tokar	Late Miocene (10 Ma)–Recent	10	1500	36 157	2444	1626	88 368	58 786		63 582	925	92.5
Halaib	Late Miocene (10 Ma)–Recent	10	1000	22 138	1824	1127	40 380	24 950		59 565	419	41.9
	Total							**83 736**				
Niger	Plio-Pleistocene	5.3						332 000	46	4 961 533	67	12.6
Niger	Oligo-Miocene	28.7						386 500	54	4 961 533	78	2.7
	Total period (34–0 Ma)	34						**718 500**			145	4.3

Based on Figures 6 and 7 for the Nile Cone. Analogue calculations are also presented for adjoining sinks which are used to calibrate the source volume calculations and overall model proposed for the Nile's history. See various sections of text for full details.

river. The DEM (Fig. 1) might suggest that major rivers originally flowed through broader valleys to the east (Atbara) and through a currently dry valley west of the Nubian Swell.

Over the Darfur swell, Miocene extrusive volcanic rocks (Franz *et al*. 1994) remain in outcrop, suggesting relatively little erosion in this region. Topographic contours on this swell are near-circular with limited incision by rivers, suggesting average erosion of the same order as in the adjoining Sudan segments.

Ethiopian Highlands north

Pik *et al*. (2003) have undertaken a study over the Blue Nile and Tekeze gorges that concludes, on the basis of partial resetting of apatite helium tracks, that the cutting of these gorges commenced at 25–29 Ma. This follows uplift associated with eruption of the Afar Plume at 31 Ma and the formation of *c*. 1 km of Ethiopian relief (Sengor 2001). Assessments of volumes eroded in the catchments of these two rivers have been made by Pik *et al*. (2003) and by McDougall *et al*. (1975), using the planation surface approach. Pik *et al*. (2003) have calculated an average of 860 m erosion, with assessments by McDougall *et al*. (1975) and Gani *et al*. (2007) being broadly in agreement with this.

The location of the sink for these volcanogenic sediments is controversial in view of the low pyroxene contents seen in pre-Pliocene Nile delta sediments, which suggests Ethiopia was not supplying sediment to the Nile delta area in the Miocene. Salama (1987, 1997) suggests that the Blue Nile basin of Sudan may have acted as an internal sink capturing Ethiopian-derived sediment and that the Blue Nile river may even have once drained to the Sudd Basin (see below); however, much of the evidence he quotes, such as wells in the Blue Nile basin with 3 km of Tertiary, cannot be validated with other available data. It is, of course, quite possible that an Oligo-Miocene Blue Nile could have deposited its sediment in an internal sink and still continued to the Nile mouth as a sediment-poor river, much as the White Nile does now.

A partial resolution with the mineralogical evidence may be reached by considering the age of uplift of the Ethiopian Plateau in its current form and its likely impact on slope creation, climate and erosion rate using the principles of Allen (1997). These would suggest that high erosion rates of hard basalts would occur only on steep slopes during periods of monsoonal-style rainfall. In Ethiopia, such rainfall patterns are themselves a consequence of the creation of relief. If Bonini *et al*.'s (2005) younger date for initiation of the Ethiopian rift shoulders of 5 Ma is correct, which is consistent with recent revisions on other East African rift shoulders, then the majority of erosion and, therefore, of sediment supply should have been during the Plio-Pleistocene, when pyroxenes are seen in Nile sediments. This is further supported by the analysis of Gani *et al*. (2007), who assign the majority of erosion on the Ethiopian Highlands to the Pliocene based on geomorphological analysis.

Sudd Basin/Ethiopian Highlands south

Salama (1987, 1997) believes that sediment eroding from the southern part of the Ethiopian Highlands and from other highs north of the current Congo–Nile divide was trapped in a large internal sink covering the Muglad and Melut basins of Sudan. As described earlier, this is mirrored by the low water and even lower sediment supply currently reaching the Khartoum confluence from the White Nile. If the current contribution of water from the Victoria Nile occurred only from 0.5 Ma (see below), evaporation losses would mean that an earlier White Nile would dry up before Khartoum. During the Oligocene these basins were actively rifting, forming deep lakes (McHargue 1992), accentuating their topography and ability to trap sediment. Based on cross-sections accessible to him, Salama calculates a Cenozoic uncompacted sink volume of 680 000 km^3 in the Bahr el Arab (Muglad) Basin and 80 000 km^3 in the White Nile (Melut Basin), volumes comparable to that in the Nile Cone. Calculations on the published isopach maps of McHargue (1992) suggest the Muglad figure is an overestimate, with volumes of the order of 200 000 km^3 being more appropriate, and it should also be noted that much of this is sediment older than the supposed initiation of the Nile at 30 Ma. Hence, further work is required in this region to check that sink volumes are capable of balancing the sediment supply from at least the southern part of the Ethiopian Highlands, using comparable erosion rates as calculated for the northern segment. However, the bulk of evidence, including the present-day analogue, does not suggest any significant past sediment contribution to the Nile. Even if there were periodic river outflows over the Sudd Basin sill south of Khartoum, then the river concerned would not have been likely to carry any significant sediment load.

Victoria Nile catchment

The Victoria Nile segment is not included in Nile source volume calculations due to Pickford & Senut's (1994) interpretation that

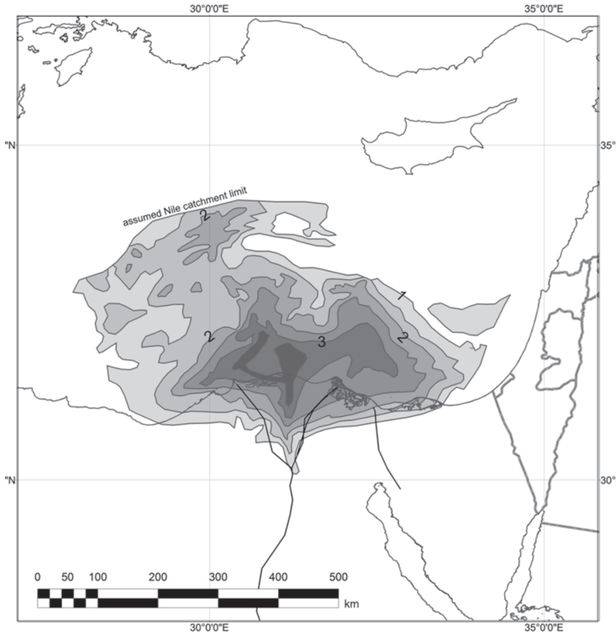


Fig. 5. Plio-Pleistocene isopach of the Nile Cone (from Hall *et al.* 2005). Contours in kilometres.

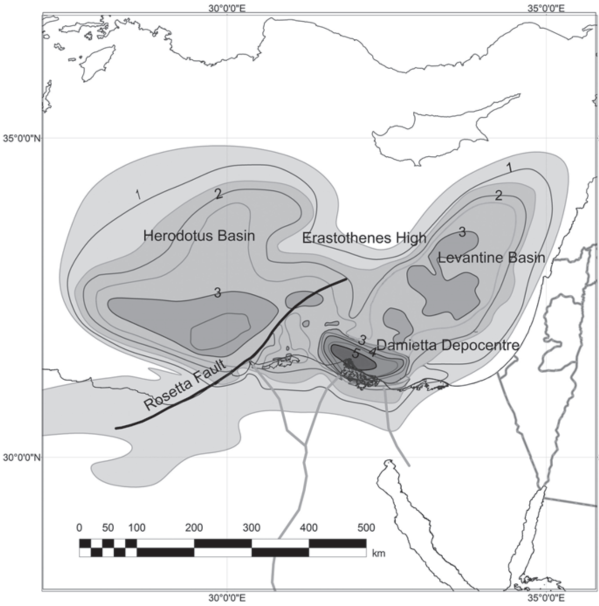


Fig. 6. Oligo-Miocene isopach of the Nile Cone, Levantine and Herodotus basins. This map is a compilation of isopach data from a variety of published sources which include (1) published structure and isopach maps in the Levantine Basin of Gardosh *et al*. (2009) and Steinberg *et al*. (2011); (2) addition of a series of published isopach maps of Abdel Aal *et al*. (1996) over the shallow-water Nile Delta area, amended with one in the Damietta region of Craig *et al*. (2011); and (3) contouring around isopachs measured from a number of published cross-sections over regions further west and offshore (Dolson & Shann 2000; Abdel Aal *et al*. 2001; Gardosh *et al*. 2009; Kellner *et al*. 2009). Contours in kilometres.

it drained into an internal sink (Lake Obweruka), periodically overflowing to the Congo, until around 0.5 Ma. Lake Victoria itself is believed to be even younger than this.

SINK VOLUME ANALYSIS: TECHNIQUES AND UNCERTAINTIES

Sedimentation rates are calculated from cross-sections (Fig. 2) while sediment volumes and fluxes are calculated from the construction of isopach maps (Figs 5, 6). Due to low time resolution in the referenced data, isopach maps in this case can only be constructed for very broad time intervals. Cross-sections usually give more time resolution. Sediment thicknesses and volumes calculated remove all porosity, using a porosity–depth trend from Sclater & Christie (1980), a North Sea compilation used frequently by basin modellers, assuming normal pressuring and an average lithological content of 90% shale and 10% sand. For a fuller discussion of methodology, see Macgregor (2012). Errors in these calculations arise from a number of factors.

(1) Poor control from published data in some regions, particularly the Herodotus Basin, where only a few schematic cross-sections have been published.

(2) Differences in stratigraphic interpretations away from or deeper than well control. Minor differences are observed where data sources merge. The pick of the critical base Oligocene event is poorly controlled and often based on regional seismic character, e.g. in the Levantine Basin, as presented in Gardosh *et al*. (2009), where it is based on seismic facies and a distant well tie across a structurally complex area.

(3) Errors in time–depth conversion and in trends applied for porosity–depth. Most sources used are depth maps, with the basis for the authors' depth conversion not known. The frequent overpressuring reported in the thickest sediments of the Nile Cone will increase porosities and, therefore, imply that compacted sediment volumes will be somewhat lower than calculated. Nashaat (1998), however, observes that significant overpressuring starts at about 2500 m, a depth by which most shale compaction has already occurred. No porosity–depth curve has been published for the Nile Delta but a comparison with the overpressured Gulf of Mexico would suggest overestimation of compacted volumes through this error of up to 10%.

(4) Effects of carbonate or other autochthonous lithologies, which should be compensated for when balancing clastic source and sink volumes. Significant carbonate content occurs at present day in Nile sediments, averaging 39% (Rifaat 2005). No calcimetry measurements are available for the subsurface. Sporadic thin discrete carbonate beds and marls are described in certain section of the subsurface of the Nile Delta, mainly in the Oligocene, Early–Mid-Miocene and basal Pliocene sections, while the Messinian Abu Madi sands contain 11% carbonate clasts (El Sisi *et al*. 1996), but other sections are not described as calcareous. On this basis, an average of 15% carbonate content is applied to the Nile sink volumes and is taken account of in the eventual source to sink balance. The considerable volumes of Messinian evaporite are not included in the isopachs on Figures 6 and 7, while other evaporite horizons are too thin to affect volumes significantly.

(5) Possible inputs from other sediment sources into the sink volume. There are none at present day. The largest additional past sediment supply to the Nile Cone probably comes from now inactive rivers debouching in SE Israel, as described by Bertoni & Cartwright (2007) and Gardosh *et al*. (2009). From their mapping, the sedimentary region affected is, however, small, *c*. 5000 km^2 during the Messinian, which is only 2.5% of the total Nile Cone sedimentary sink. Steinberg *et al*. (2011) believe that the dominant contributor in the

deep-water Levantine Basin is the Nile. Again, some overestimation results, probably of a few percent.

(6) Losses by aeolian mechanisms of sediment deposited temporarily in internal sinks, which are unquantifiable. This will include all the volume of desert sand in the Western Desert and all the fines winnowed out by winds and now deposited as loess in distant sinks. Volumes could be significant, leading to an underestimate of total sink volume associated with the Nile.

(7) Dispersal of bathyal sediment to regions outside the calculated area and volume, where they are mixed with sediment from other sources. Sediment thicknesses below 1000 m for the Plio-Pleistocene and 500 m for the Oligo-Miocene are not considered in the calculations, covering areas of likely mixed sediment sources covering large areas of the Eastern Mediterranean. The volumes of Nile contributions over such excluded areas could be significant and will cause an underestimation of sink volume. Indeed, Woodward *et al.* (2007) show that present-day Nile sediment influences extend as far as Rhodes, Crete and to the north of Cyprus. In addition, coastal drift may well transport Nile-derived sediments northwards beyond the assumed sink areas.

Many of these errors are systematic and others random. Those that are more likely to result in underestimates (6 and 7 above) are thought to be more significant than those likely to result in overestimates (3 and 5 above), so the sink volumes calculated may be more likely to be underestimates than overestimates. Carbonate content is the least well controlled of the uncertainties at present.

SINK VOLUME ANALYSIS: CALCULATIONS (TABLE 2)

Compacted sediment volumes in the Nile Cone are calculated from two isopach maps covering the Plio-Pleistocene (Fig. 4) and Oligocene to Miocene (Fig. 5) periods. These volumes are separated into deep-water regions by volumes of Messinian salt. The former map is taken from Hall *et al.* (2005), is controlled at key drilled locations, such as the Abu Madi area of the Nile Delta, and also agrees with separate interpretations, such as that of Gardosh *et al.* (2009). The Oligocene–Miocene isopach map is a new less well-controlled compilation assembling isopach data from a variety of published sources listed on the figure caption. 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 maps give estimates for total compacted volumes of 188 000 km^3 for the Plio-Pleistocene and 393 000 km^3 for the Oligo-Miocene. These compare with independent interpretations, made from extrapolation of cross-sections by Robin *et al.* (2011), of 330 000 km^3 and 396 000 km^3 for these two intervals (calculated from a sediment flux histogram with carbonate content removed). The reason for the large difference in the Plio-Pleistocene is not known, but clearly Robin *et al.* (2011) did not use the isopach map of Hall *et al.* (2005).

At this time, stratigraphically higher resolution isopach maps cannot be produced. More detailed stratigraphic resolution is, however, possible using published cross-sections, from which compacted sedimentation rates profiles can be calculated for a number of intervals (Fig. 2). These show surges in depositional rate correlatable with a number of key climatic and tectonic events in the hinterland. The two lobes on Figure 6 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 Damietta depocentre (Fig. 6) has up to 10 km of Oligocene–Recent fill (Craig *et al.* 2011), including a particularly thick mid–late Oligocene marking the onset of Nile clastic deposition in this region, commencing at 30 Ma, with prograding commencing at 27.5 Ma. Offshore and onshore Nile Delta seismic data both evidence a major change in sedimentary facies over a major unconformity within the Oligocene. Dolson *et al.* (2002) illustrate a major downcutting unconformity over the offshore Herodotus Basin that correlates to a change from carbonates to channelized clastics onshore, while a seismic section offshore Levantine Basin in Gardosh *et al.* (2009) appears to show NE-directed downlaps over a similar unconformity. These features are thought to tie to a sharp initiation of the Nile drainage system, close to Craig *et al.*’s (2011) date of 30 Ma.

INTERPLAY WITH OTHER AFRICAN DRAINAGE SYSTEMS (FIGS 7, 8)

Authors such as Issawi & McCauley (1992) and Goudie (2005) have proposed that the Niger originally had a much larger catchment than present day, which covered much of the current Nile catchment. This interpretation of a ‘Trans-Africa Drainage System’ is supported here for the Paleocene–Eocene section, where offshore African sedimentation is dominated by the Niger, suggesting that the Niger system captured headwaters from much of Africa at the time (Macgregor 2012, fig. 12). The comparison of sedimentation rates in the two depocentres (Fig. 7), as measured from a number of published cross-sections, suggests a shift in sedimentation from the Niger to the Nile in the Oligocene. From the Miocene onwards, the offshore sedimentation rates and trends are seen to be similar. Explanations for the drainage change during Oligocene time include the uplifts of the Uweinat swell, as dated by Late Eocene volcanics, and the Afar Plume uplift, dated at 31 Ma. The initiation of these and other African uplifts likely changed drainage patterns across the continent (Burke & Gunnell 2008; Macgregor 2012). The similarity in the two profiles from the Miocene onwards suggests that erosion over the entire northern Africa region was pulsed in response to wide-ranging controls of similar age, which suggests a strong climatic control over regions of similar latitude and/or a less explainable synchronicity between the various Neogene uplifts affecting the region.

Figure 8 presents a map of Oligocene sedimentation rates around Africa, taken from Macgregor (2010). It can be seen that sedimentation rates in the Nile are amongst the highest seen on African margins, comparable to those on the Niger and in excess of those on the Congo. By comparison with the other systems mentioned, the Nile would appear to require a large hinterland extending well south of Egypt. This is expanded further by back-calculating average erosion rates by dividing sink volumes by catchment area (Table 2). If the White Nile is excluded, the apparent denudation rate of the Blue Nile catchment is over double that of the Niger. If the area of the Blue Nile catchment south of Egypt was transferred to the Niger, as proposed by Issawi’s & McCauley’s (1992) Miocene river reconstructions, the comparison becomes unsustainable. The erosion rate on Egyptian rift shoulders would then have to be in excess of 80 m Ma^{-1}. Logically, similar rates would have to be applied to the regions of Sudan and Eritrea transferred to the Niger, which then would be interpreted to provide the majority of the Niger sink volume in the Miocene and would then have to contrast with very low denudation rates elsewhere in the Niger catchment. Given similarities in topography and climate along latitude lines, this seems unlikely.

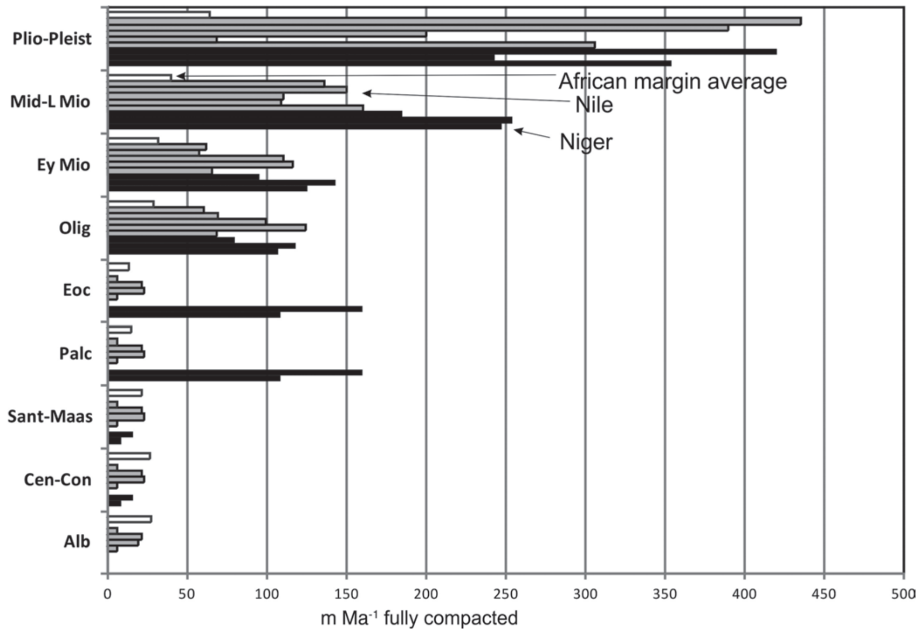


Fig. 7. Compacted sedimentation rates for published cross-sections in the Nile and Niger deltas and cones. Source data for the Nile (grey fill) from top to bottom are from: Robin *et al*. (2011); cross-section of Dolson *et al*. (2000) over central cone; cross-section of Kellner *et al*. (2009) over western cone; cross-section over Levantine Basin of Gardosh *et al*. (2009); cross-section of Abdel Aal *et al*. (2001) over central cone. Those for the Niger (black fill) are from Robin *et al*. (2011) and calculated from sections over the west and east delta by Haack *et al*. (1997). The averaged African rate (white fill) is calculated by the author from 50 points around Africa, mainly published cross-sections (see Macgregor 2010, 2012). Note the increase in Nile rates relative to the Niger and to average African rates in the Oligocene, suggesting a drainage switch at that time.

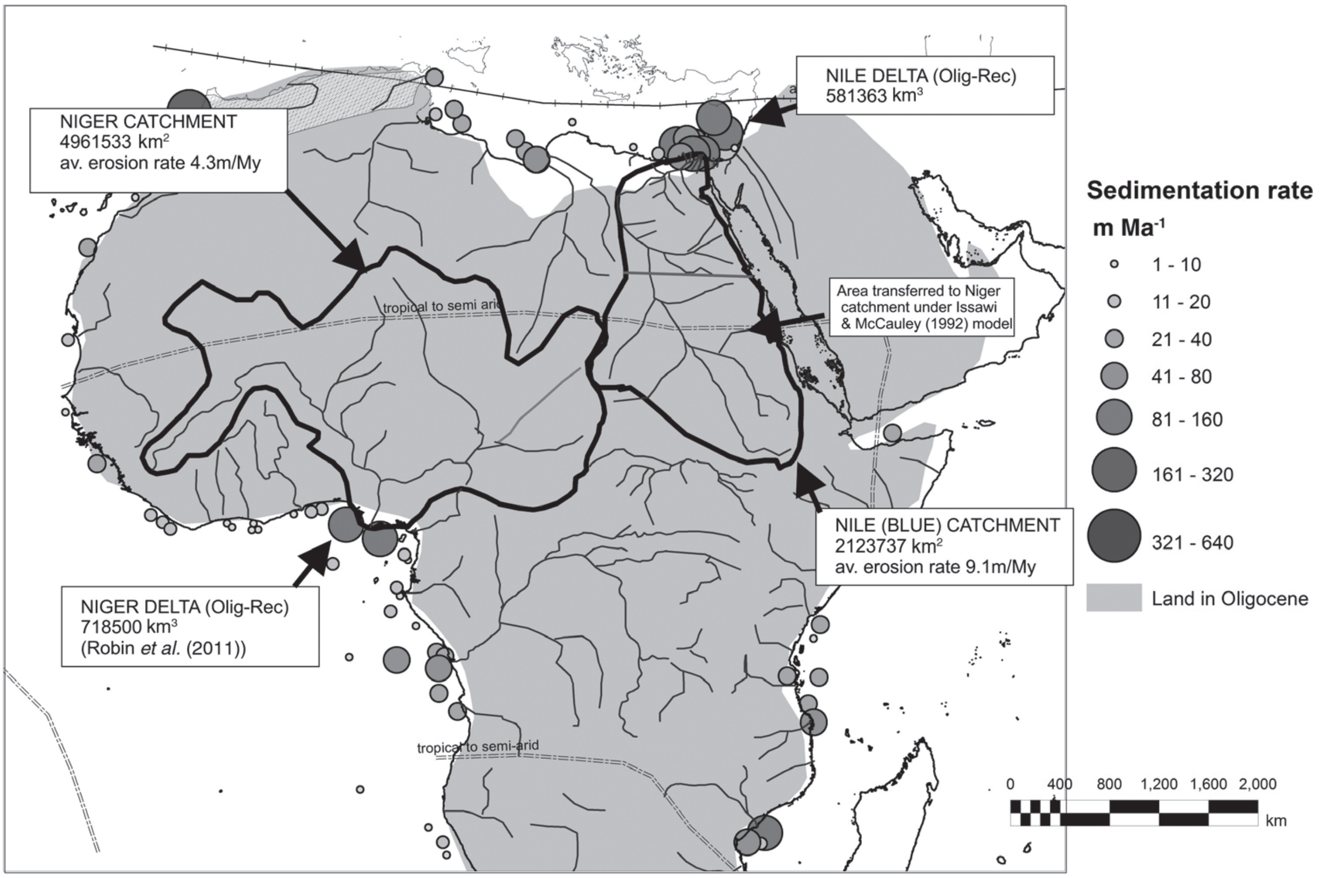


Fig. 8. Oligocene sedimentation rates around Africa, amended after Macgregor (2010). Note high rates in Nile area, with only the Niger and a small delta off the Atlas showing comparable rates. This indicates that a major river, with a large catchment comparable to that of the Niger, must have been established at this time. Climatic lines amended after Morley (2007) and Scotese (2011).

SOURCE TO SINK VOLUME COMPARISONS

We are now in a position to compare the calculated sink and source volumes of the Nile for the Oligocene (30 Ma)–Recent period. The right-hand columns of Table 1 and Figure 9 present a number of attempts to balance source and sink volumes. Four models (Issawi & McCauley model, Cases 1–3 from data in this paper) are initially prepared for source volumes without attempting a balance to sink volume. A fourth model presents the author's best case resolution matching the calculated sink volume.

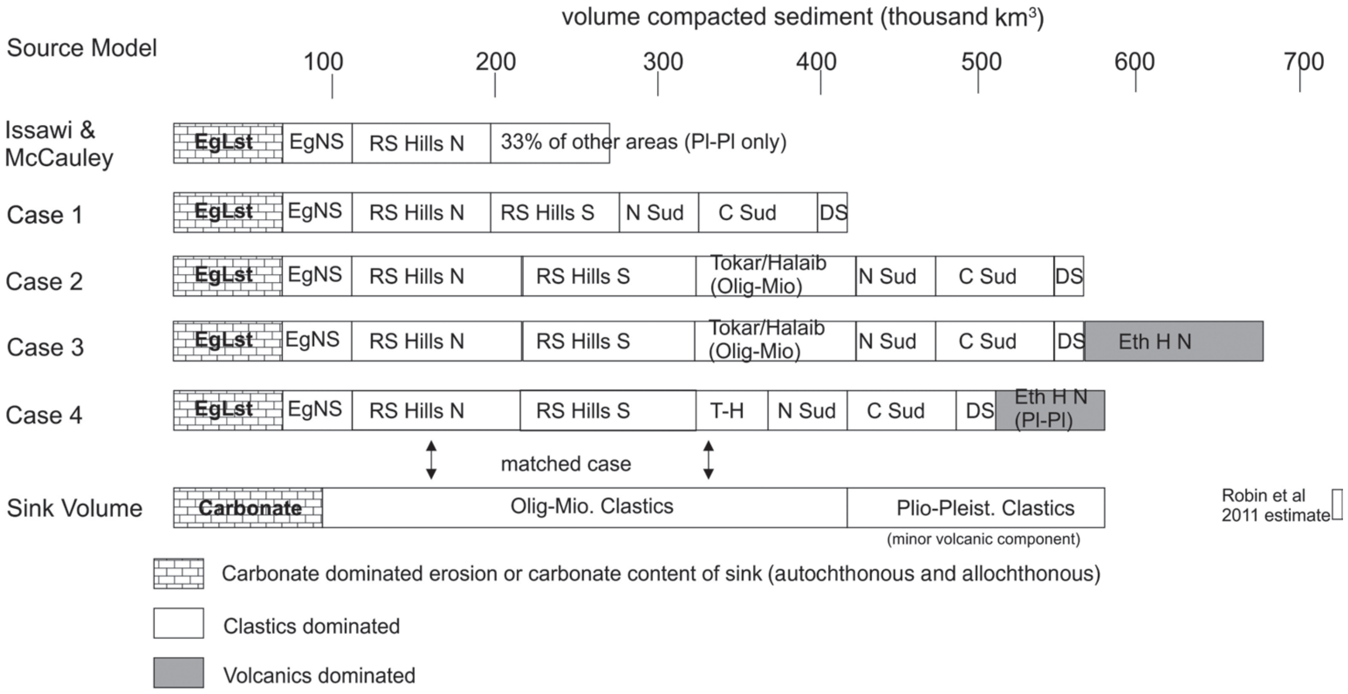


Fig. 9. Volumes calculated in this paper for sources and sink portrayed as a series of combined models. Previously published models can be rejected as feeding insufficient sediment to the Nile Cone. Inclusion of an upside erosion model (see text) for the Red Sea Hills and/or inclusion of the Ethiopian Highlands is required to balance sink volumes. The best solution fitting the sink volumes and other available evidence is presented as Case 4. See text for further explanation.

The 'Issawi & McCauley' case allows only Egyptian segments to contribute to the sink up until the Plio-Pleistocene and other segments to contribute thereafter. Southern segments are allowed to contribute a third of their calculated total eroded volume, representing an estimated contribution in the Plio-Pleistocene only, based on the age distribution of the sink volume. This is, in fact, an upside case of their interpreted drainage history as, in the Miocene, they have much of the region considered draining to Chad and the Niger. Eroded thicknesses and rates in the Red Sea Hills northern segment have to be more than doubled over those estimated in this paper in order to match the sink volumes, implying original altitudes of Egyptian Red Sea shoulders of *c.* 5 km. If this was the case then all the AFTA points should be showing Cenozoic fission track ages.

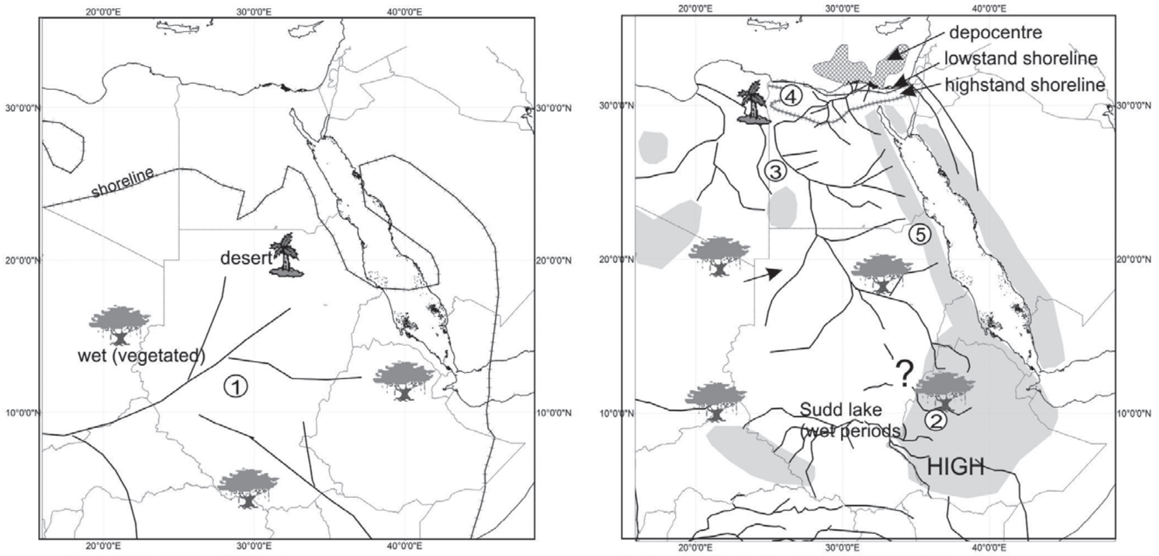
Case 1 shows the combined calculation for all segments north of Ethiopia and adopts the lowside source volume calculation described for the Red Sea Hills. This leads to a 30% shortfall to the sink volume. Case 2 adopts the upside Red Sea Hills source calculation and then more or less matches the sink volume. However, as stressed in the discussions for this region, this is an extreme case. Case 3 adds in the Ethiopian Highlands north segment for all time periods (in violation of the mineralogical evidence) and gives a figure which exceeds the most likely sink calculation.

Case 4 is a 'most likely' case that is forced to match the sink volume and, it is believed, gives the best agreement with onshore geological, tectonic and mineralogical evidence. The Red Sea volumes used are intermediate between the upside and downside cases described, with relatively little pre-10 Ma sediment volume being transferred from the Tokar–Halaib catchments, while 70% of the sediment eroded from the Ethiopian Highlands north is included. This figure is consistent with a model for which only Plio-Pleistocene sediment from this region reached the Nile, being triggered at about 5 Ma by uplift of the Ethiopian Rift shoulders, with an associated sharp increase in maximum rainfall and erosion rate (Gani *et al.* 2007).

CONCLUSIONS (FIG. 10) AND PETROLEUM IMPLICATIONS

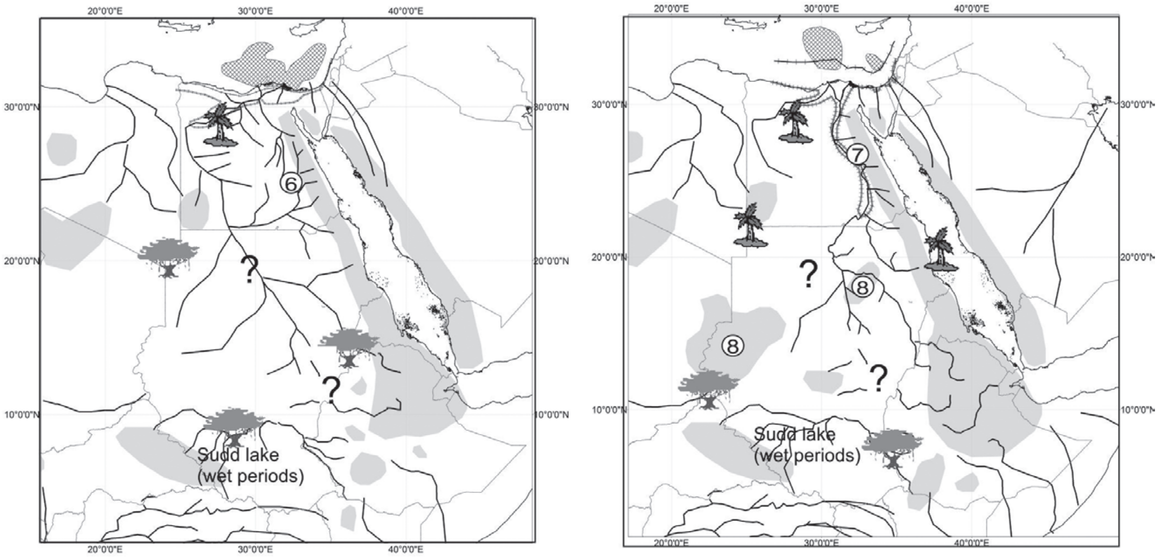
Evidence from sedimentation rates and volumes in the Nile Delta and Cone, together with a synthesis of onshore evidence and an attempt at a source to sink solution suggests that the river must have had a large catchment from its origin around 30 Ma. Amendments must be made to the proposed river histories of both schools of authors described in this paper's introduction, with the reconstructions of the first school not matching sink volumes, and those of the second school inconsistent with mineralogical

Fig. 10. A most likely history of the Nile drainage system, based on evidence presented in this paper and the literature. Contemporary relief highs in grey. Palm trees denote dry climate; deciduous trees denote wet climate; hatching offshore indicates main sinks. Major changes labelled include (1) Eocene Trans-Africa drainage system supported by relative sedimentation rates between Nile and Niger; (2) Pik *et al.* (2003) interpretation of initial cutting of Blue Nile canyon through rising Afar Plume in Oligocene, though sink for this system at this time is uncertain; (3) Gilf system of Issawi & McCauley (1992) connected to a Sudanese river to explain high offshore sedimentation rates; (4) Dolson *et al.* (2002) Oligocene incised valley system connected to Gilf; (5) rise of Red Sea rift shoulders to provide main clastic sediment source thereafter; (6) Miocene Qena river system of Issawi & McCauley (1992) connected to a palaeo-Atbara rather than to a Benue–Niger system; (7) creation of Eo-Nile in Messinian, after Said (1981); (8) initial rise of Darfur and of ?Nubian swells from 14 Ma, based on volcanic ages of Franz *et al.* (1994); (9) preferred young interpretation of uplift of Ethiopian rift shoulder at *c.* 5 Ma; (10) creation of modern Sahara desert, pushing area of active erosion southwards and lowering Nile Cone sedimentation rate over previous wet phase; (11) Nile course changes in still rising Nubian Swell area (Thurmond *et al.* 2004) to create current immature 'Cataract Nile'; (12) rising East African rift shoulders divert previous Congo headwaters (Pickford & Senut 1994) to create Victoria Nile, causing overflow from Sudd Basin to create a periodically connected White Nile.



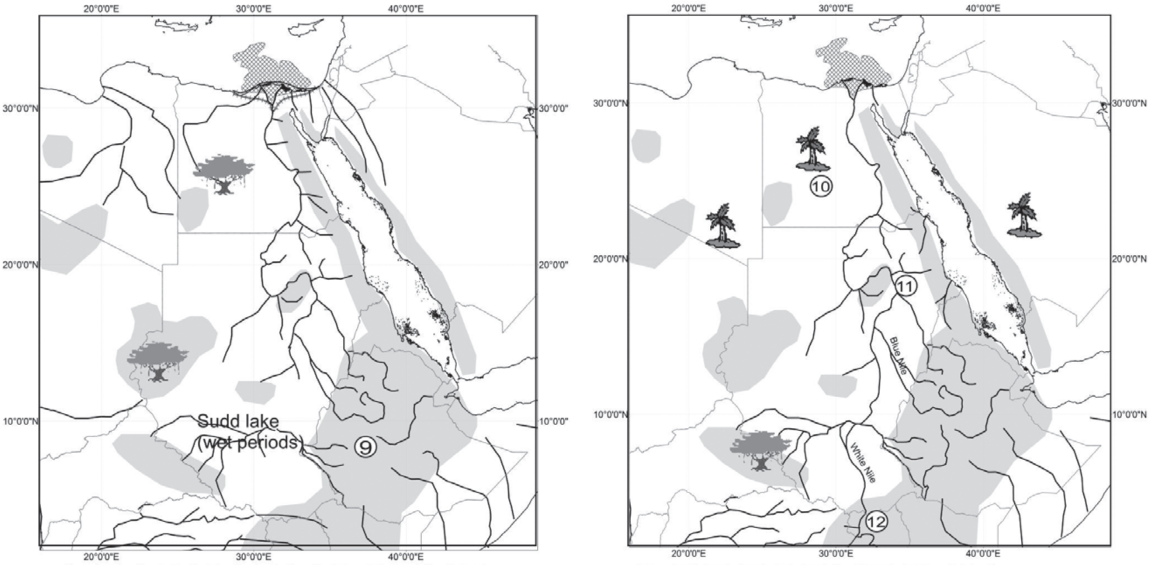
a) EOCENE

b) OLIGOCENE



c) EARLY MIOCENE

d) MESSINIAN



e) EARLY PLIOCENE

f) PRESENT DAY

evidence in the pre-Pliocene section. A compromise between these two extreme models is adopted here and is presented in Figure 10. This solution can be summarized in the following way.

Red Sea rift shoulders, which supply about half the clastic sediment contribution to the system, are suggested to have first risen at 30 Ma, more or less contemporaneously with the Afar Plume, triggering the formation of the Nile system as represented by a sharp change from carbonates to clastics in the Nile Delta. The rise of these rift shoulders and other contemporaneous 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. Sudanese and Eritrean rivers flowing down the Red Sea rift shoulder eventually connected with the 'Gilf' system of Issawi & McCauley (1992) and thereafter with a series of incised valleys in the Western Desert (Dolson *et al*. 2002). The location of the sink for Pik *et al*.'s (2003) proposed Oligocene Blue Nile is uncertain on present evidence. Abdelkareem *et al*.'s (2012) interpretation that the Nile flowed south–north up the Qena valley does not seem likely as the Red Sea rift shoulders were already rising at this time. Issawi & McCauley's (1992) Miocene 'Qena' system can be preserved over much of its extent but it did not continue into Chad, but instead probably switched northwards into the 'Gilf' course, cutting the escarpments of the Western Desert and Qattara Depression. The timing of switch into the 'Eo-Nile' course (through Aswan) of Said (1981) could have happened any time between the Early Miocene and Messinian. Large surges of sediment from Ethiopia commenced around 5 Ma as the rift shoulders there rose with an associated increase in rainfall. It is probable that late uplift of the Nubian swell deflected the river system (Thurmond *et al*. 2004), with earlier routes possible both to the east and west. The White Nile is probably a recent addition and has never been a significant contributor of sediment.

Isopach mapping indicates a Nile Cone geometry during the Oligo-Miocene that was more controlled by pre-existing structure than the recent more typical delta shape. This geometry undoubtedly influenced deep-water reservoir deposition in areas such as the Levantine Basin. The high sedimentation rates and existence of a western river input for long periods of the Oligo-Miocene would suggest that reservoir potential in the deep-water Herodotus Basin should be high. The base of the Nile clastic reservoir system and its prospectivity lies within the Oligocene, at around 30 Ma. The Niger sediment system, where turbidite sands are also known to extend hundreds of kilometres from the shelf edge (e.g. outcrop section on São Tomé island), appears to have a very similar sediment supply pattern to the Nile and is a good analogue for predicting deep-water Nile reservoirs. Perhaps the most important perception of this study for exploration for deep-marine reservoirs in Africa as a whole is that current sedimentary patterns are not always indicative of the past. Thus, a significant sand supply may have existed previously from hinterlands now temporarily experiencing arid climates. Predictive models for such settings must, therefore, take more account of changes in modelled climate.

F. Guillocheau and D. Robin of the University of Rennes 'Topo-Africa' project are thanked for contributing their sink calculations on the Nile and Niger deltas. Two anonymous reviewers are thanked for constructive comments.

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Received 18 October 2011; revised typescript accepted 1 June 2012.

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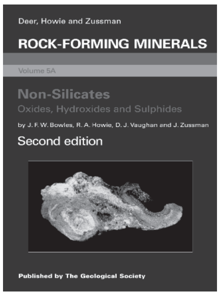
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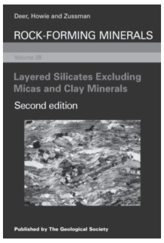
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