Understanding African and Brazilian Margin Climate, Topography and Drainage Systems, Implications for Predicting Deepwater Reservoirs and Source Rock Burial History*

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Introduction and Methodology

A GIS database has been compiled containing locations of key indicators of uplift, denudation, sedimentation, igneous activity and climate across the whole of Africa and the conjugate margin of Brazil since the Albian. The purpose of this compilation is to develop the interpretation of patterns of continental uplifts, palaeo-topography, denudation and drainage systems that most closely honours these indicators. This can then be used in turn to identify implications of petroleum systems; i.e., to predict hidden turbidite systems offshore through sedimentation rate - lithology relationships and better understand source-rock burial history onshore.

Africa has long been documented to show a 'basin and swell' structure (Burke et al., 2003, 2008; Figure 1), and similarities to the topography of eastern South America have also been noted. King (1962) documented the existence of uplifted peneplanation surfaces on both continents (Figure 2), of which the best known are the African surface and the South American surface; both can be observed on topographic maps to have undergone significant erosion. It is these erosion products that form the bulk of the Cenozoic fill on the margins of the two continents. The most recent analyses, based partly on the latest AFTA data (Figure 3), interpret the African surface to have been cut as a low peneplain in the latest Cretaceous to Eocene and then uplifted/eroded from Oligocene onwards (Burke and Gunnell, 2008), while the South American surface may be older, possibly uplifted in the Palaeocene in SE Brazil (Tello et al., 2003), with erosion from Eocene onwards.

Similarities in the topographic and erosional history of Africa and Brazil are seen in the sedimentary response along the margins (Figures 4 and 5). In particular, a change from carbonate and argillaceous sediments to prograding coarse clastics can be noted at the base of the Oligocene in many

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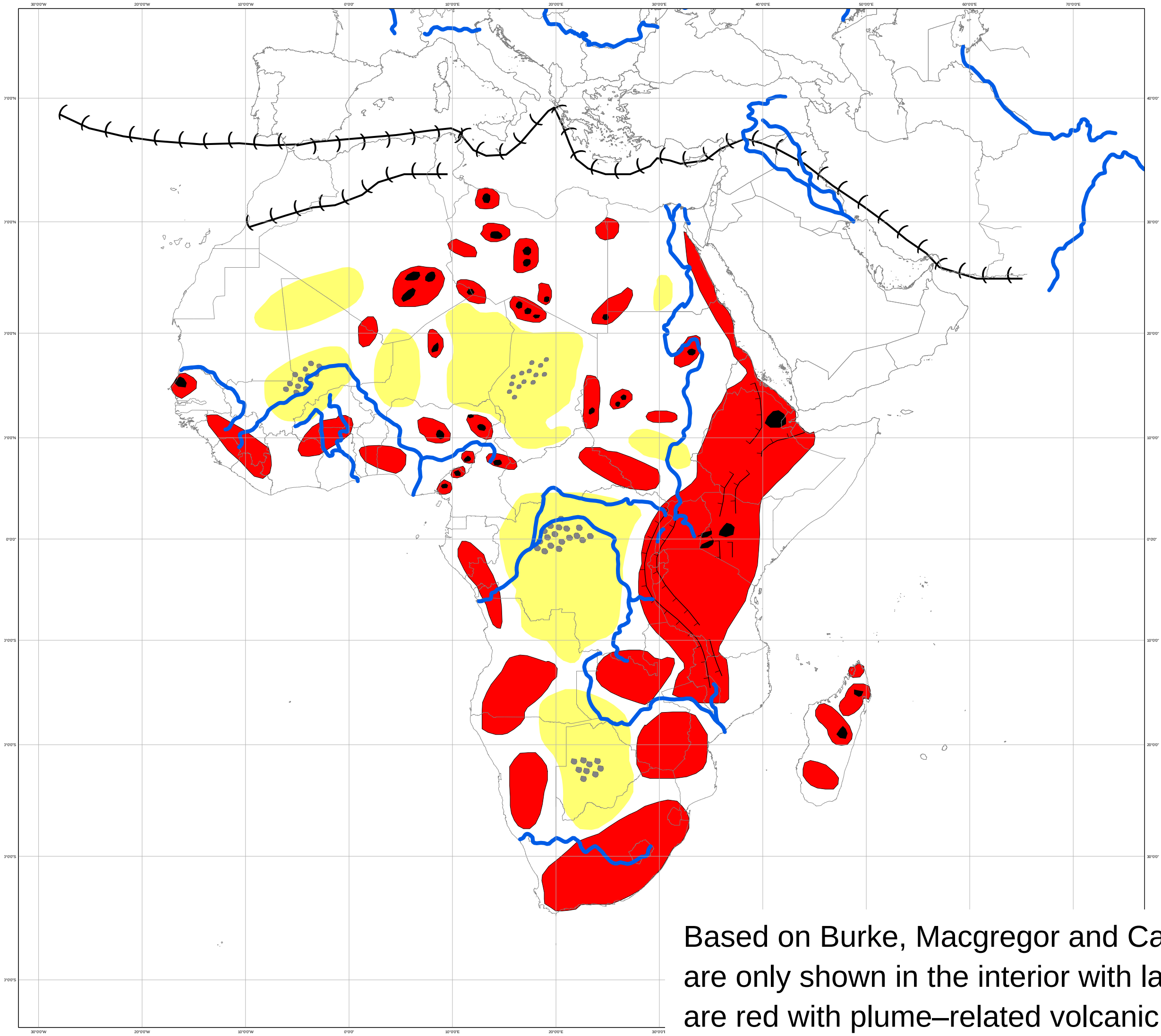
African basins. This trend is also seen as the 'regressive' Oligocene to Recent sequences interpreted on Brazilian margins (Milani et al., 2007). As a critical part of this study, over 100 points have been constructed as sedimentation-rate profiles (Figures 6 and 7), calculated from a similar number of published or internet cross-sections and isopach maps of varying quality. These are converted to fully compacted rates using standardised porosity-depth (Schlater and Christie, 1980) and velocity-depth relationships (Walford et al., 2005, see this reference for full details of methodology). The letters assigned to the profiles on these figures reflect the nature of and level of confidence in the source data, classified as such: A= isopach maps, B= set of seismic lines or cross-sections, C= detailed single cross-section, D= schematic single cross-section, E= well or point based. Category A profiles integrate a number of more localised published calculations (e.g., Walford et al., 2005, Leturmy et al., 2003, Laville et al., 2001, Rouby et al., 2008), which are in good agreement with the new work. Comparison of the different source data in well controlled basins allow an assessment of the errors involved in such calculations, and it is observed that these give good agreement in the relative profile of sedimentation rates over time within a basin. Comparison of the precise calculated rates between basins at specific times require that several independent data sources, preferably of Categories A-C, are used, and the calculated sedimentation rate differences are significant. Where the sedimentation rate analyses are based on Categories D and E or show wide variations, as is particularly the case for the Brazilian margin (Figure 7), greater credence is given in the analysis to other evidence, particularly progradational trends, which are fortunately well documented in this region (Milani et al., 2007).

For the purpose of this study, a GIS database has been compiled containing locations of indicators of uplift (unconformities), denudation (AFTA), climatic indicators (bauxites, evaporites), igneous activity together with the sedimentation rate and progradational patterns discussed above. Climatic indicators in this study are taken largely from Gunnell (2003), Burke and Gunnell (2009) and Scotese's PALEOMAP Project. AFTA data comes from Balestrieri et al. (2009), Cobbold et al. (2009), Foster and Gleadow (1996), Gallagher et al. (1998), Hackspacher et al. (2004), Jackson and Hudec (2005), Morais Neto et al. (2008), Omar et al. (2009), Pik et al. (2003), Raab et al. (2005), Tello et al. (2003), Turner et al. (2008), and Walgenwitz et al. (1992). The Brazilian margin studies as noted have relied heavily on stratigraphic data and sections in Milani et al. (2007) and Bizzi et al. (2003).



Drafting by Stuart Jessop, courtesy of Neftex Petroleum Consultants

Based on Burke, Macgregor and Cameron 2003. Basins, yellow, are only shown in the interior with lake deposits in gray. Swells are red with plume–related volcanic rocks in black. Major rivers in blue

Figure 1. Basin and Swell Structure of Africa.

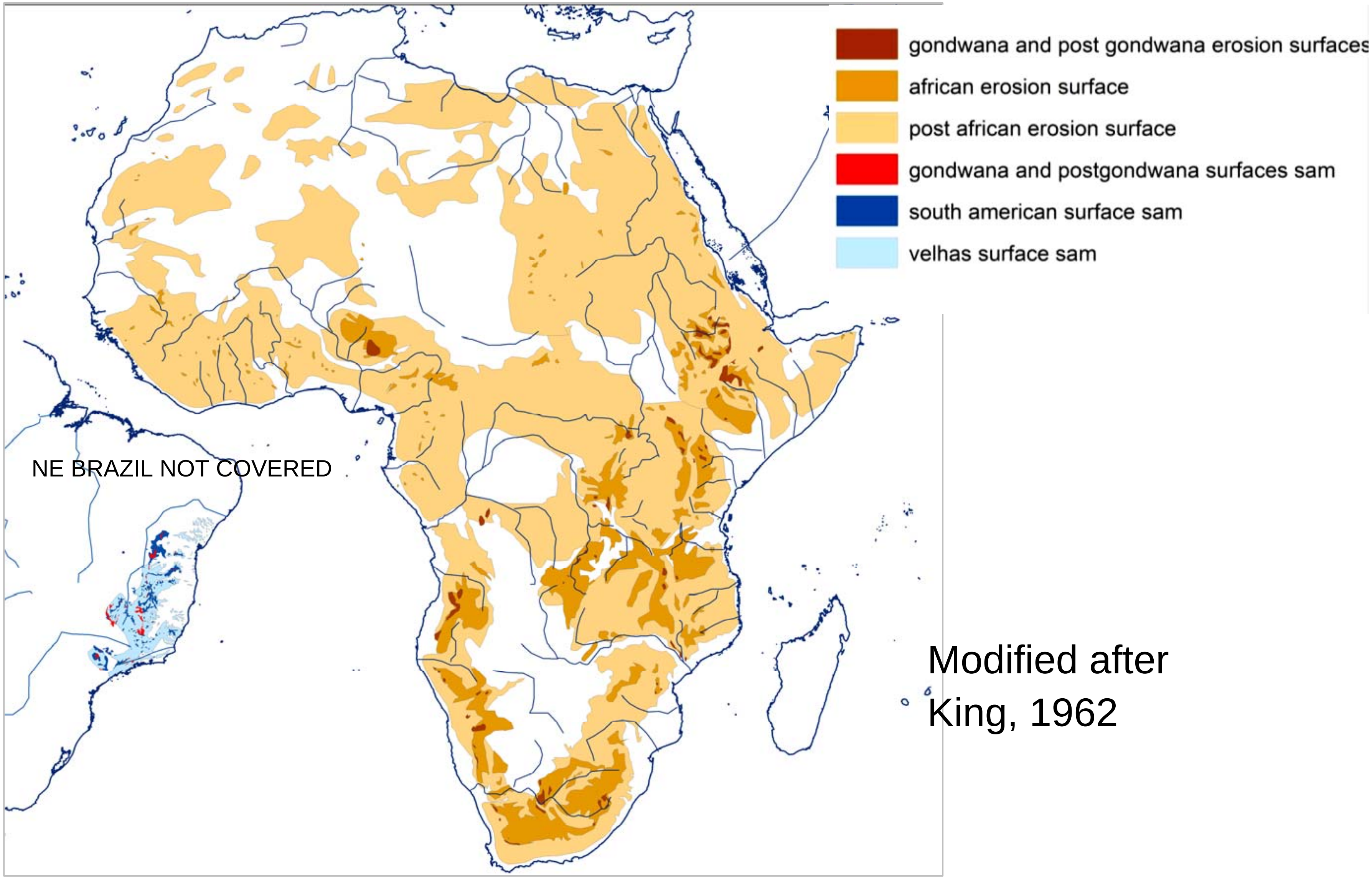


Figure 2. Peneplanation Surfaces and Neogene Drainage.

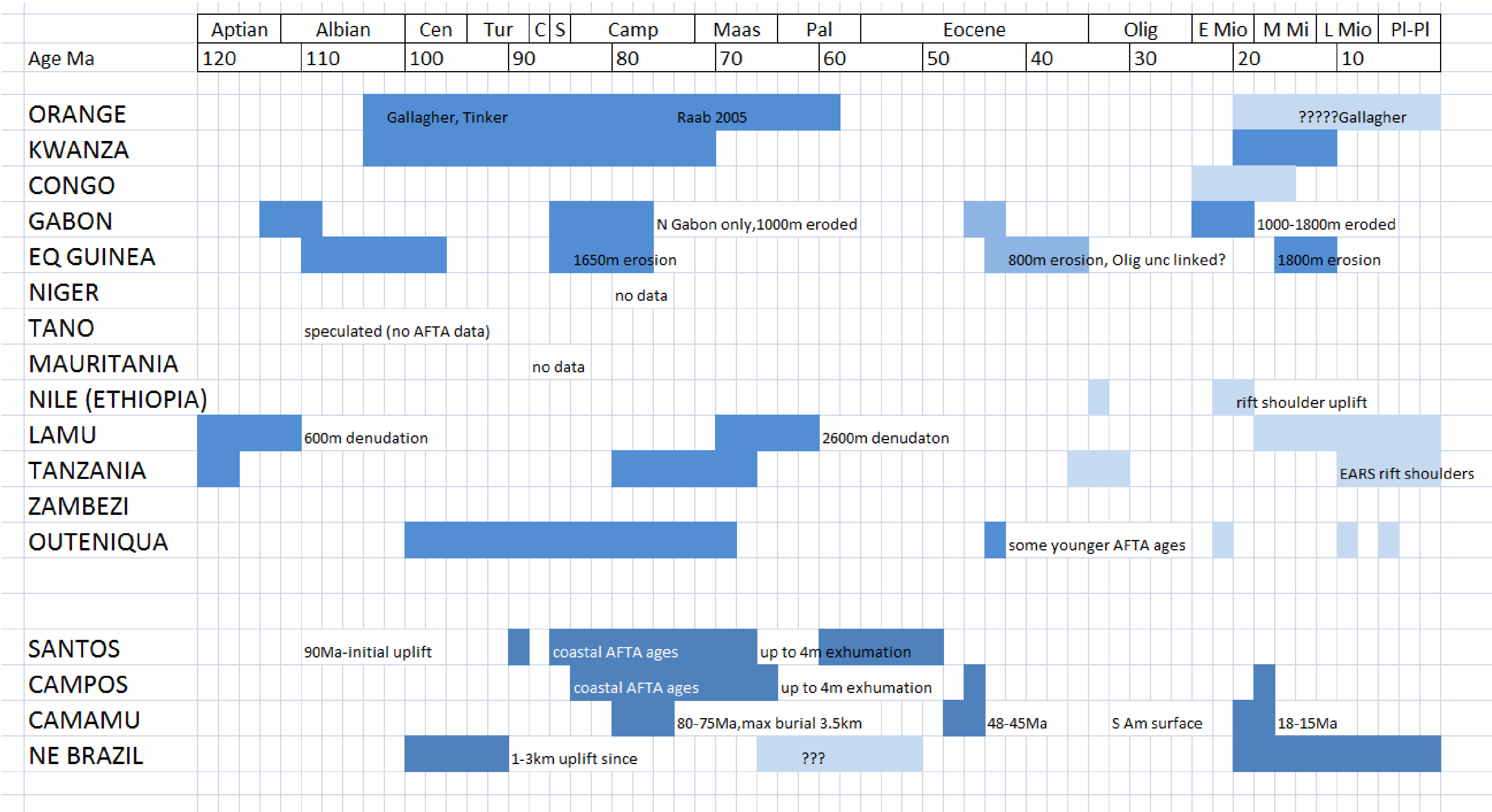


Figure 3. AFTA studies summary.

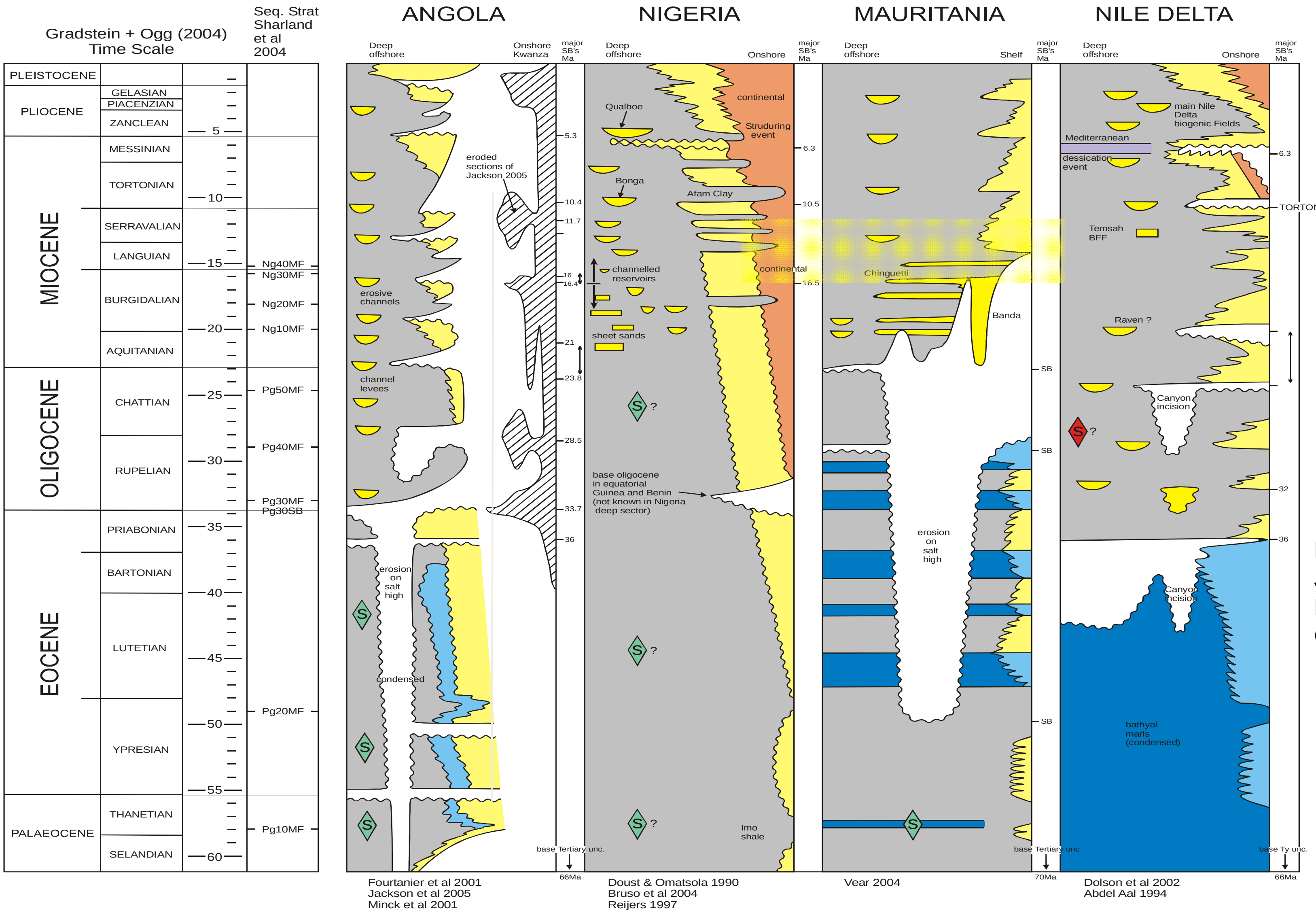


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Figure 4. Progradation: Tertiary correlation of major deltas and fans.

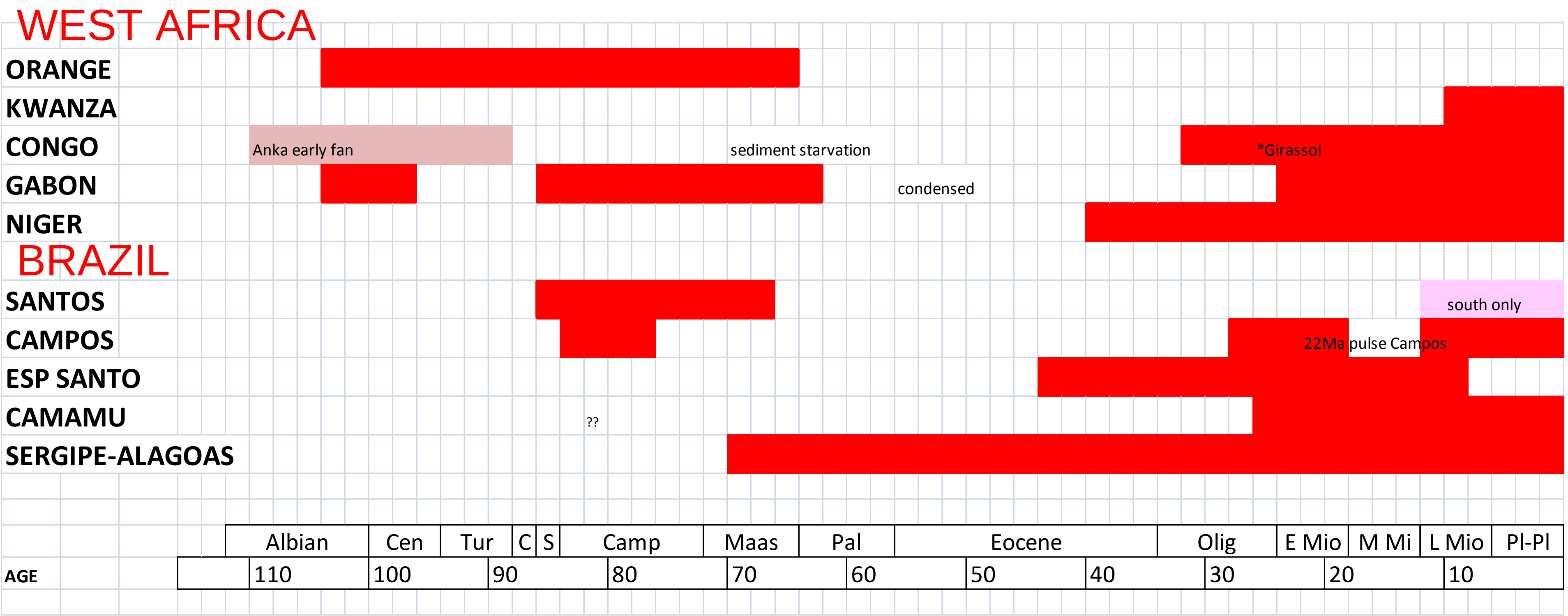

Figure 5. Progradation trends through time.

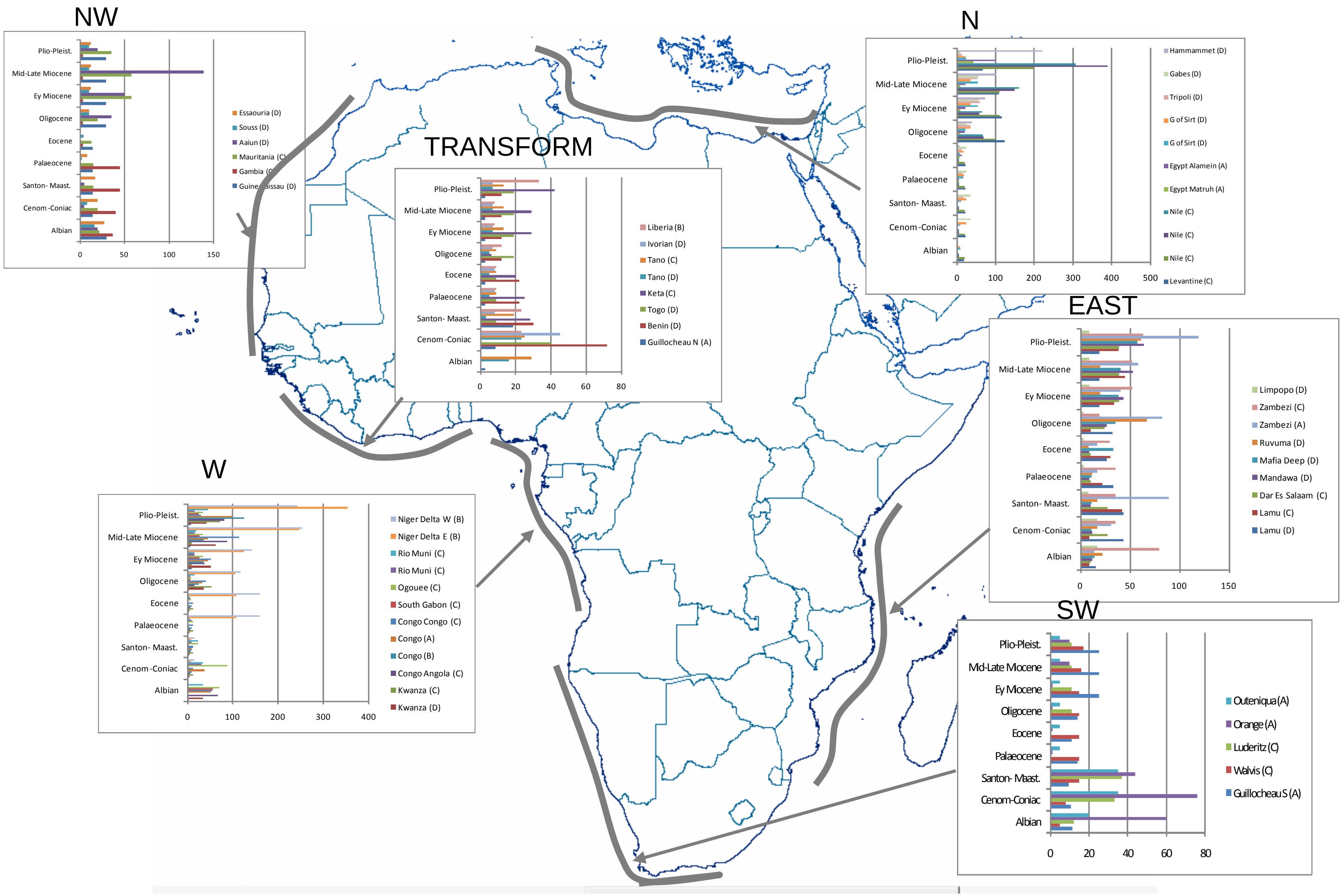

Figure 6. Regional African sedimentation rate profiles.

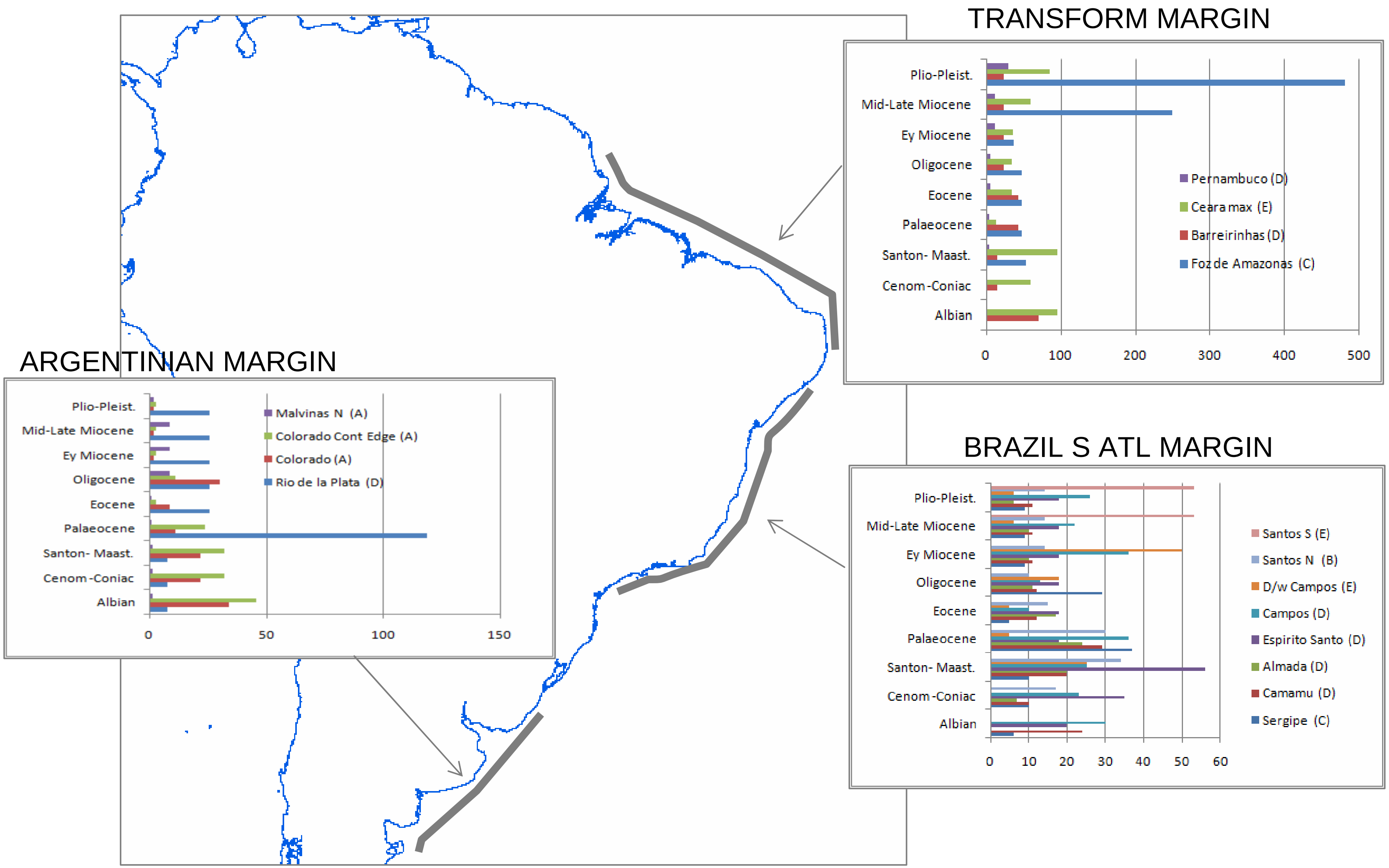

Figure 7. South American Atlantic sedimentation rate profiles.

Basis of Interpretations

The database described above is plotted on a series of maps (Figures 8, 9, 10, 11, 12, 13, 14, 15, and 16) from which relationships can be drawn. With particular reference to the Plio-Pleistocene (Figures 8 and 9) and to a lesser extent the Palaeocene-Eocene maps of Africa (Figures 13 and 14), two levels where our understanding of the climate and topography of Africa is relatively well controlled, the following paradigms can be drawn and applied to other intervals:

1. Arid climates are tied to low sedimentation rates, as at Present Day (Figure 9). Exceptions of rivers debouching into such arid settings with high sedimentation rates can be tied to sediment input from high wet regions upstream; e.g., 80% of current Nile sediment comes from the Ethiopian highlands.

2. The combination of topography and wet climates, e.g., in the Ethiopian Highlands and in much of the present Niger river catchment at Present Day, result in the highest sedimentation rates. A strong climatic control is clearly evident on Figure 9, with high sedimentation rates confined to rivers that erode areas of high topography within regions of high current run-off. It can be noted on Figure 9 that practically all depocentres with high current sedimentation rates tie to river catchments at least partially in high regions within the line of significant run-off extended from that published by Goudie (2005).

3. The wide marine transgressions seen over North Africa in the Palaeocene and Eocene (Guiraud et al., 2005), accompanied by widespread bauxite and laterite developments (Gunnell, 2003), indicate that most of Africa was low and flat at that time and characterized by low denudation rates, despite a wet climate (Figures 13 and 14). Bauxite and laterite developments in northern Brazil are consistent with this picture. Low topography thus also ties to low denudation and sedimentation rates, at least at this time of low seasonal climatic variations and high sea levels.

4. The periods of uplift indicated by offshore unconformities dipping basinward from the highs, uplifted marine and peneplanation surfaces, and more indirectly by AFTA denudation dating and high sedimentation rates, often tie to periods of igneous activity. This is best illustrated in the western Sirt Basin, where unconformities and structural thinning ties to igneous activity on the Tibesti and other highs. The nature of igneous activity, however, differs in nature over time. Alkali volcanism characterizes the Oligocene and younger ‘swells’ of interior Africa, with increasing frequency towards younger dates (Ebinger and Sleep, 1998). In contract, less frequent kimberlite pipes (Figures 15 and 16) characterize the Late Cretaceous uplift of the South African plateau. The continental margin uplifts, however, lack significant volcanism.

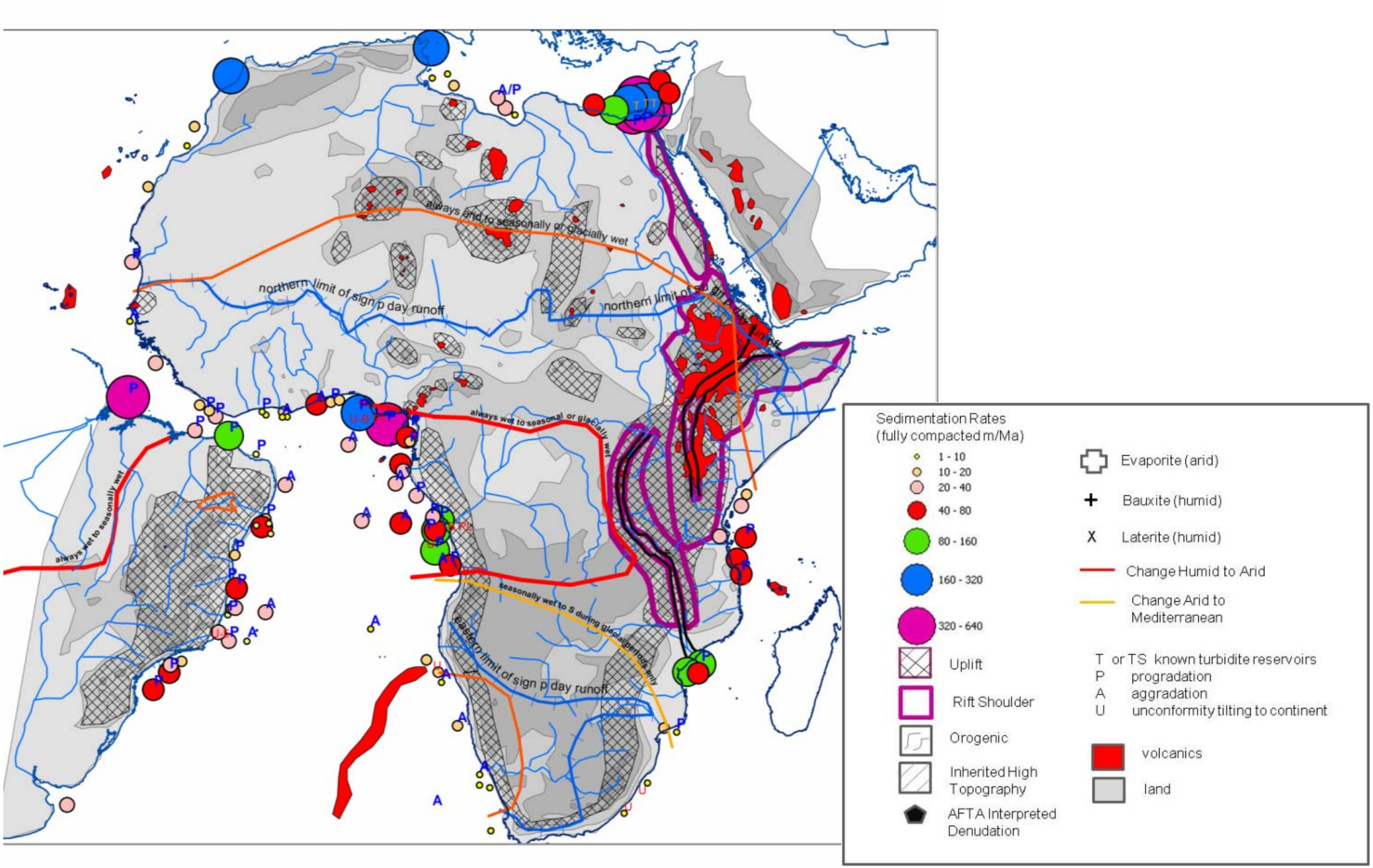

Figure 8. Plio-Pleistocene sedimentation and climatic topographic controls.

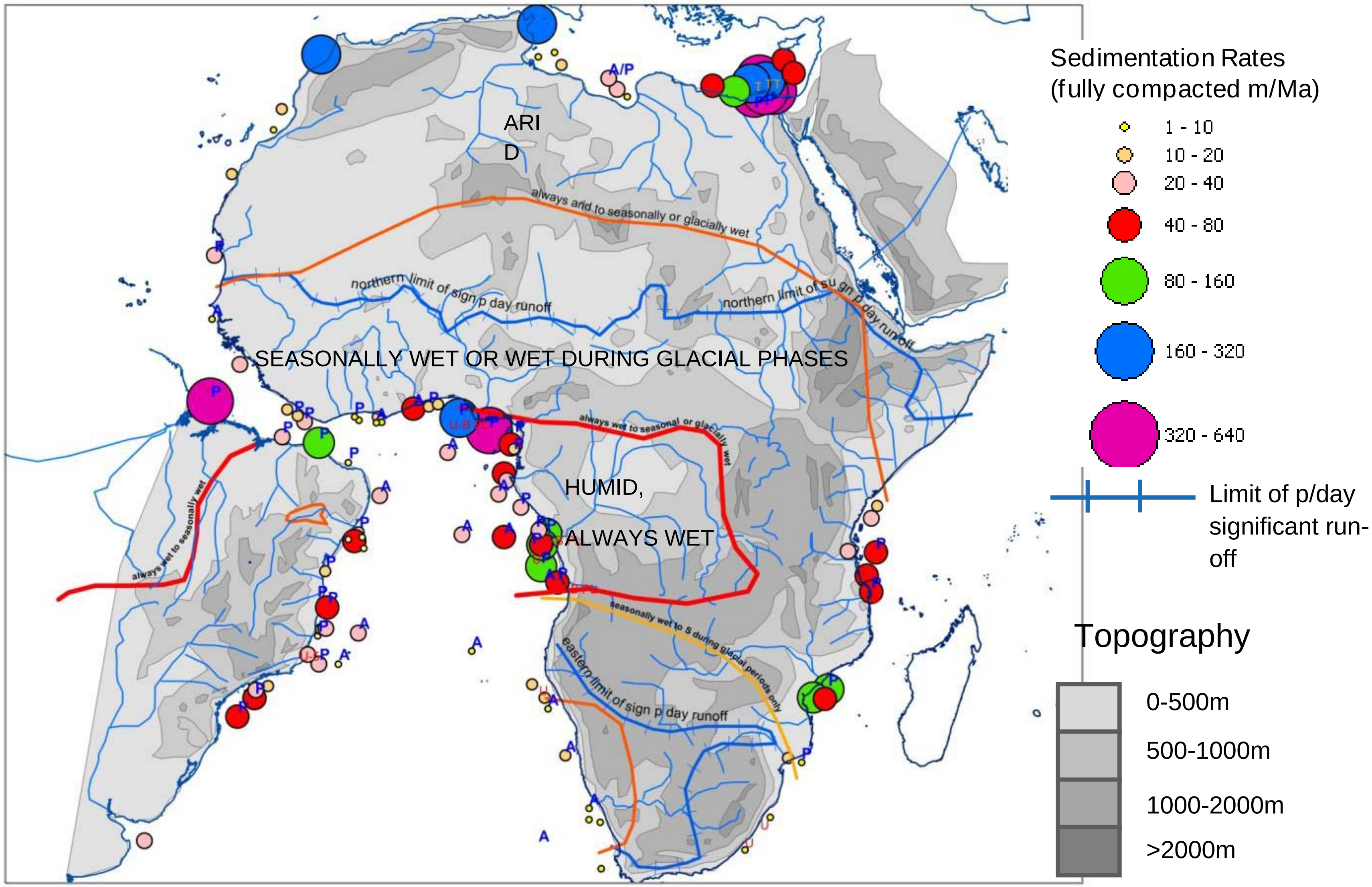

Figure 9. Recent climatic and topographic controls vs. Plio-Pleistocene sedimentation rates.

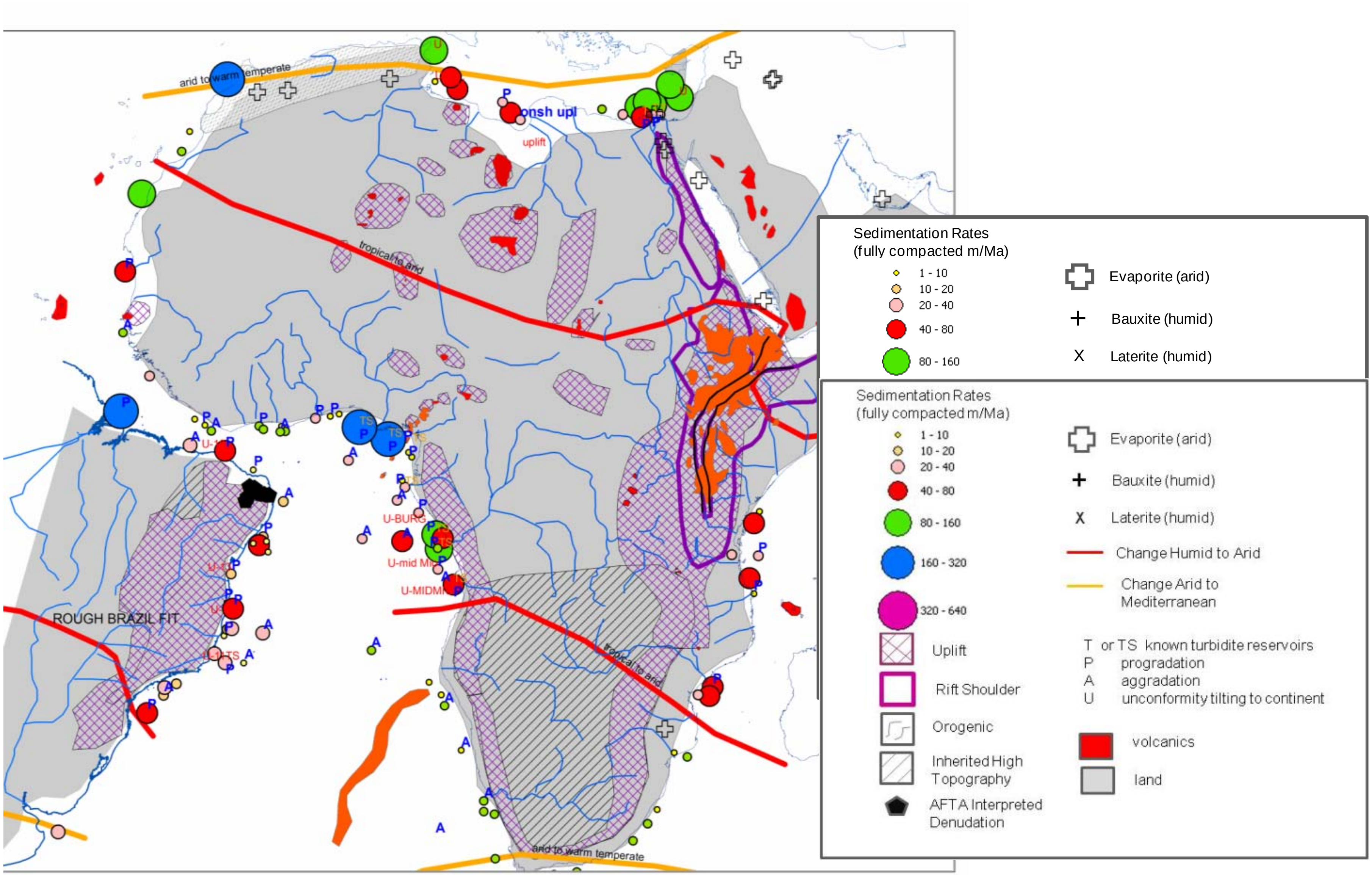

Figure 10. Mid-Late Miocene sedimentation and climatic topographic controls.

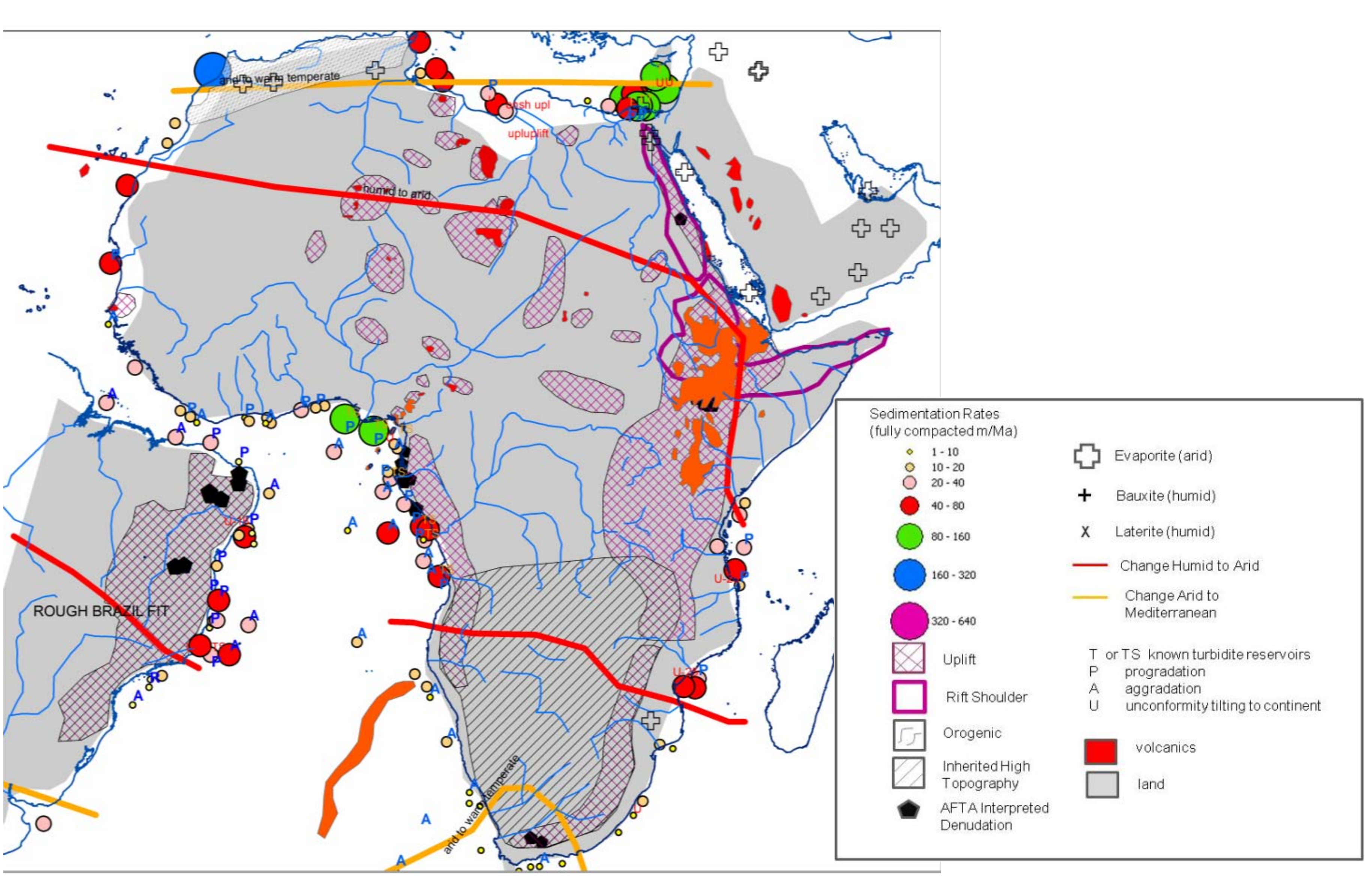

Figure 11: Early Miocene sedimentation and climatic topographic controls.

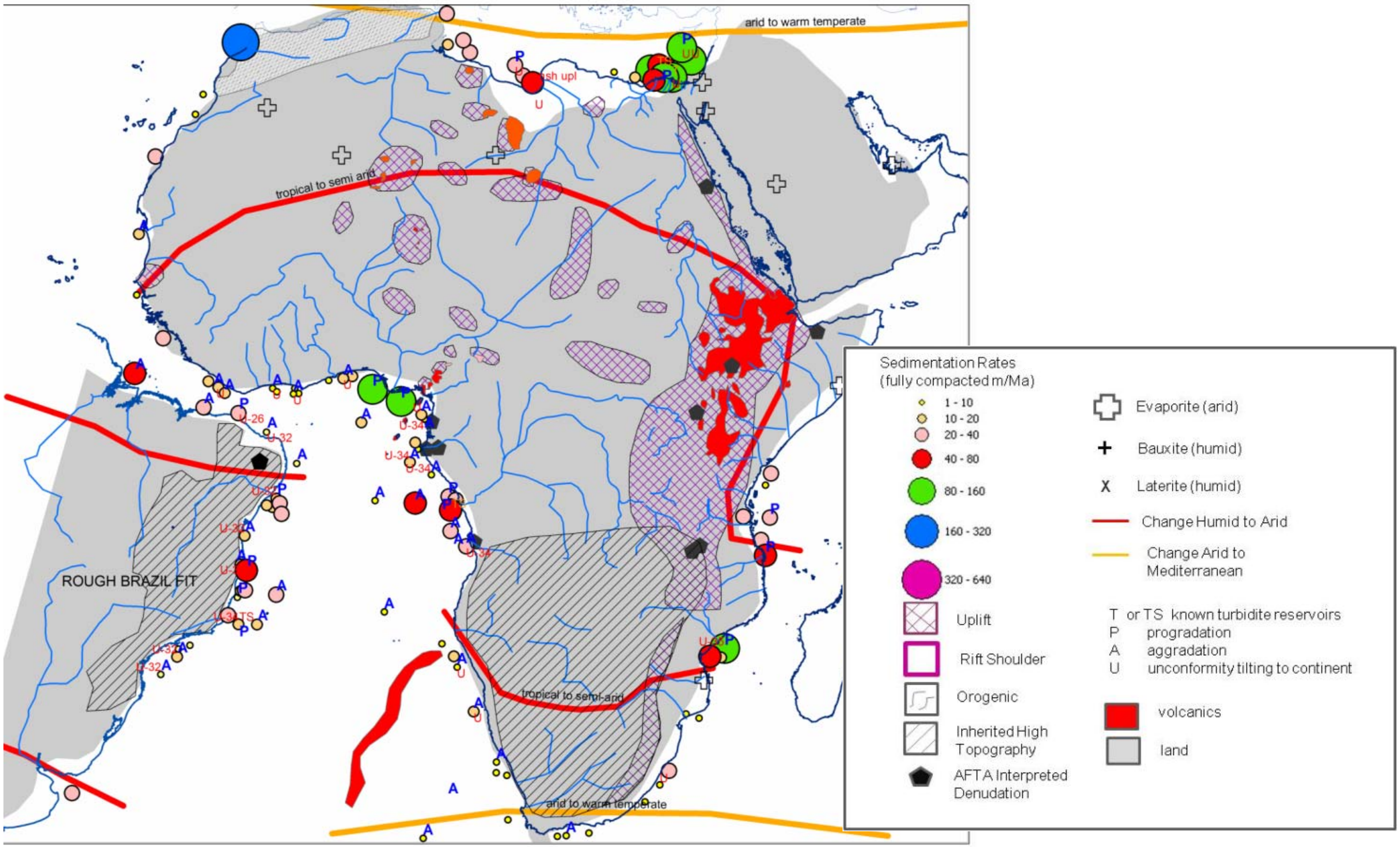

Figure 12. Oligocene sedimentation and climatic topographic controls.

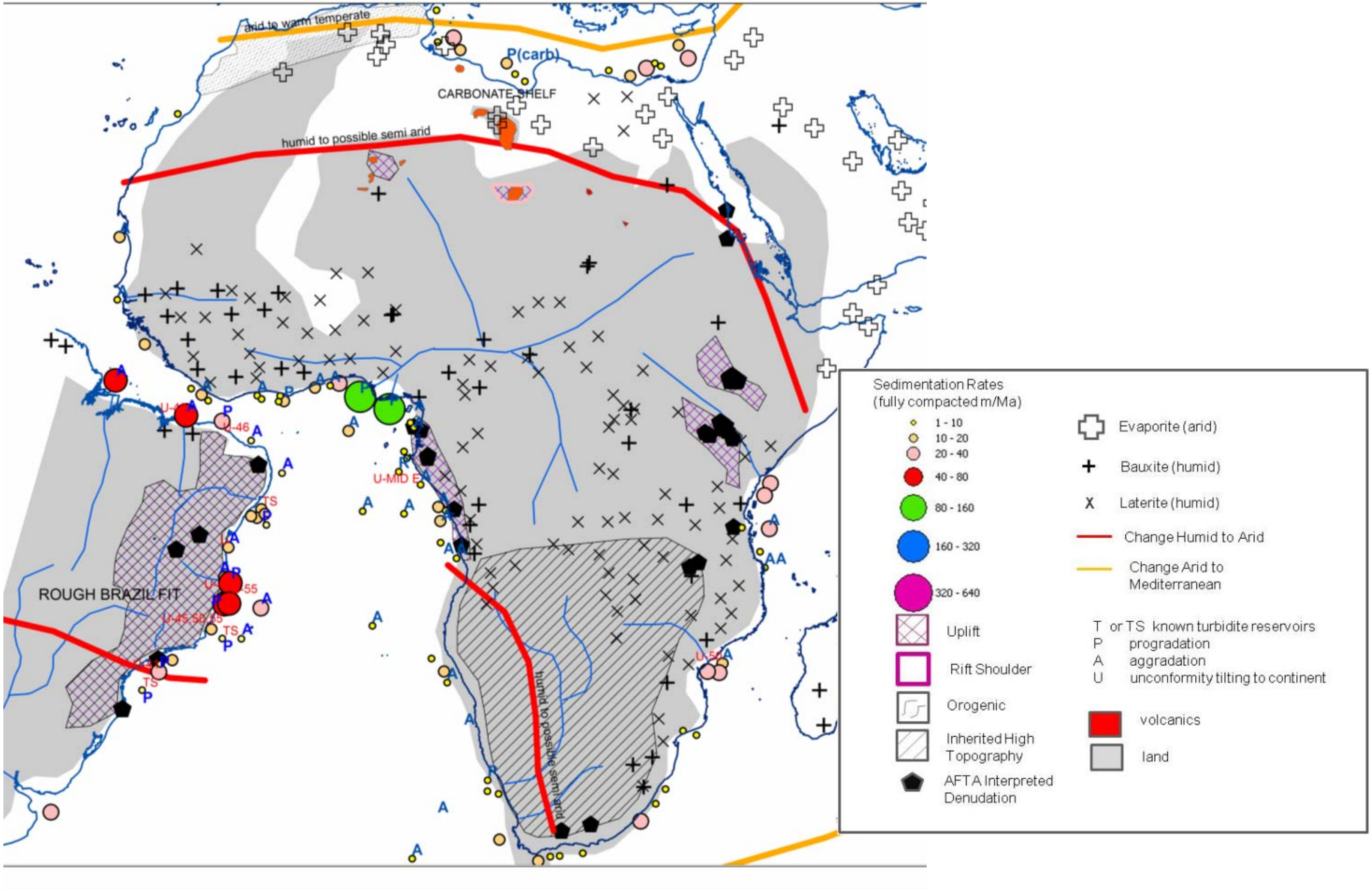

Figure 13. Eocene sedimentation and climatic topographic controls.

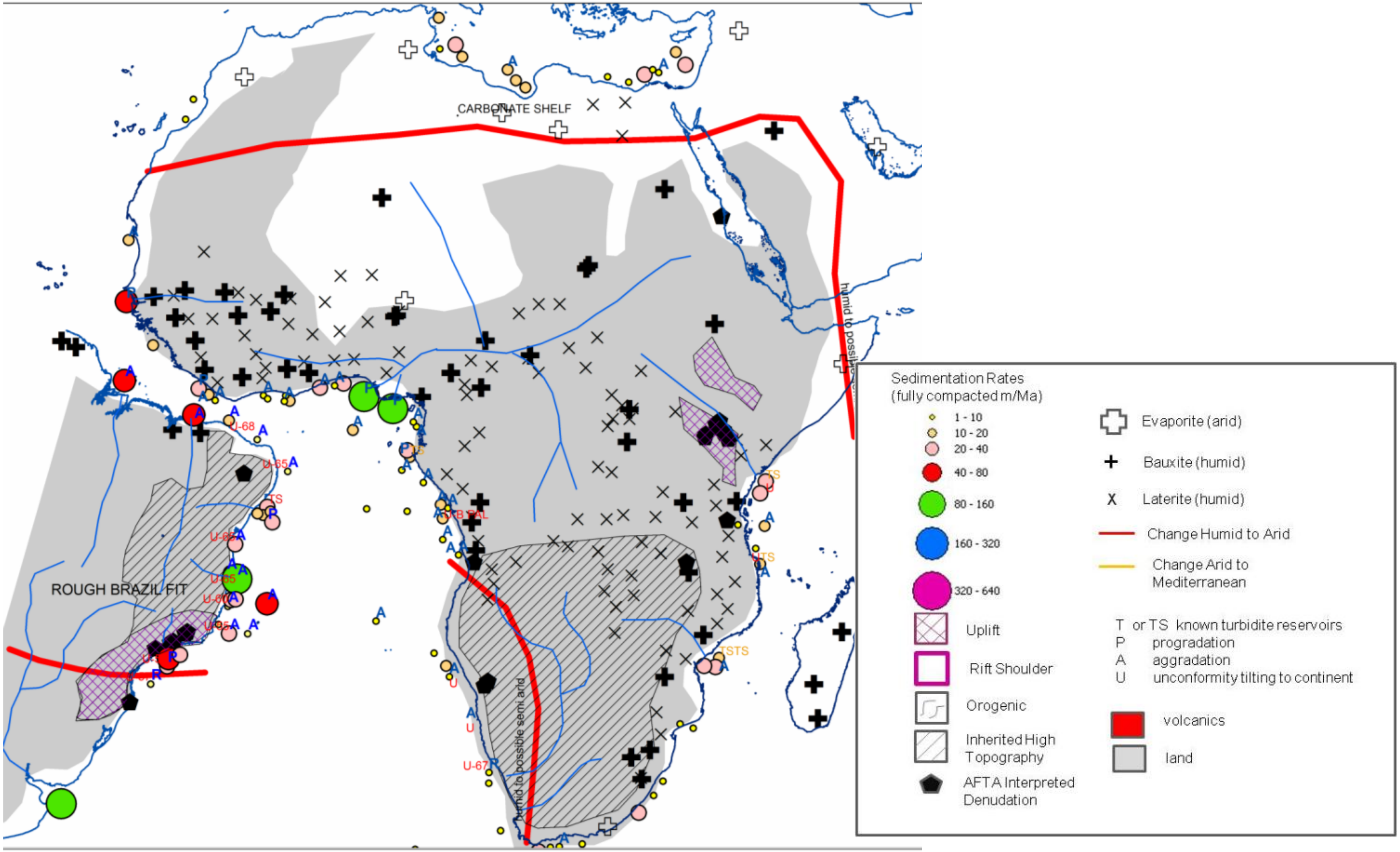

Figure 14. Palaeocene sedimentation and climatic topographic controls.

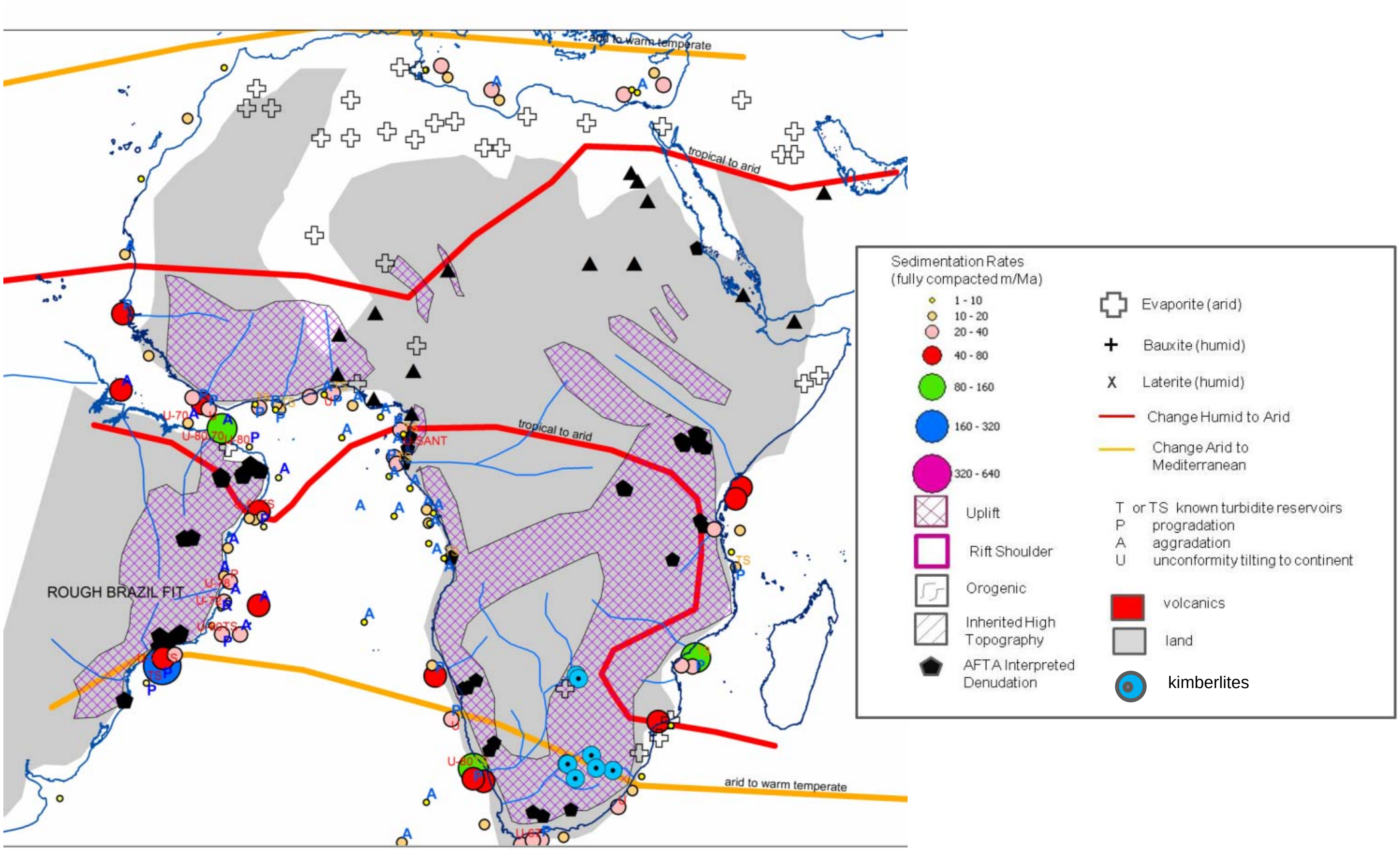

Figure 15. Santonian to Maastrichtian sedimentation and climatic topographic controls.

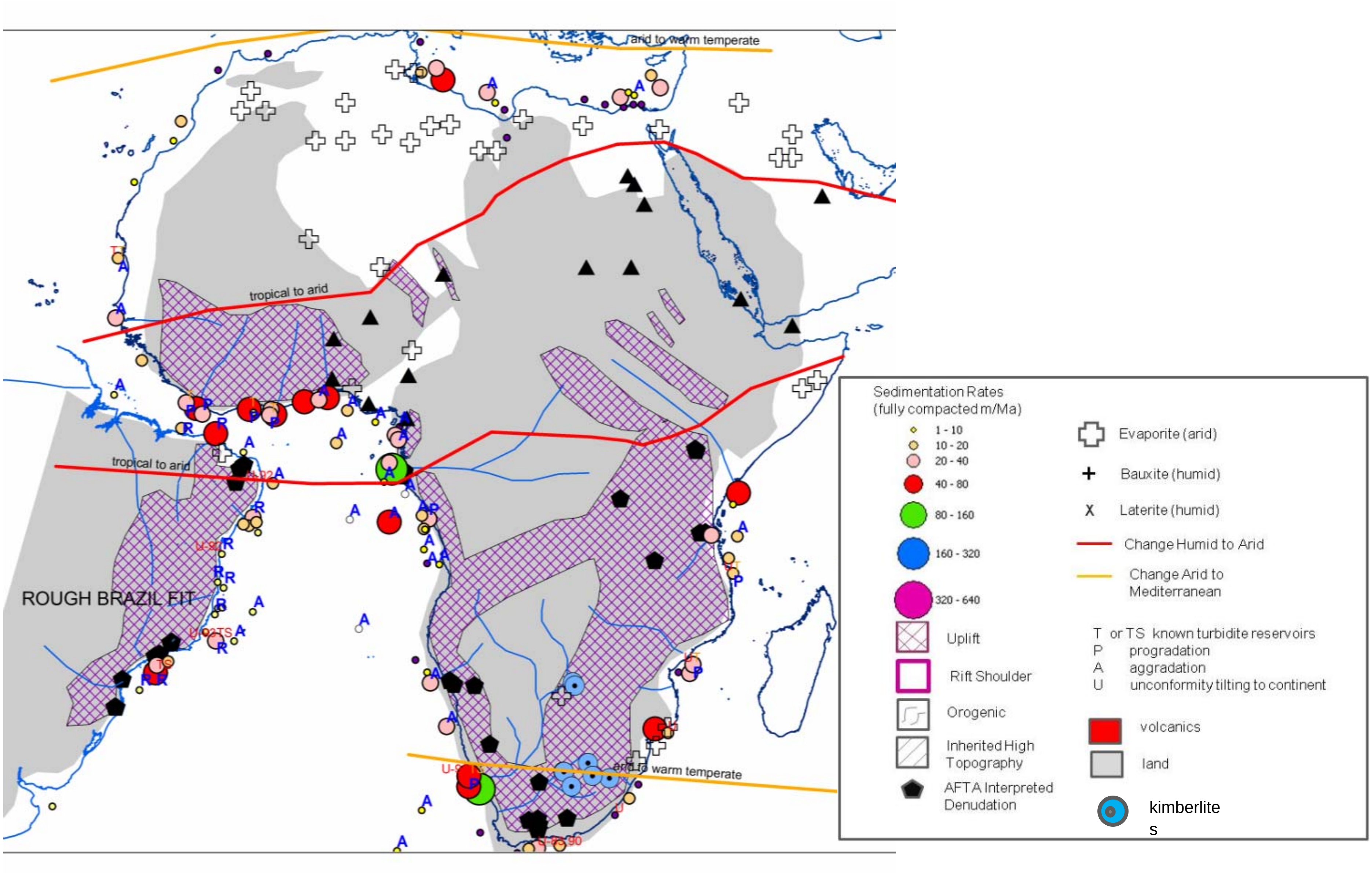

Figure 16. Cenomanian to Coniacian sedimentation and climatic topographic controls.

Interpreted Development of Africa and Brazil through Time

Application of these paradigms, particularly the requirement for both significant topography and wet climates to feed high sedimentation rates, allow best fit interpretations to be made on Figures 8-16. These are largely a modification of broader published interpretations; e.g., Burke and Gunnell (2008) for uplifts, and Scotese (2010) for palaeoclimate, with changes made to fit the indicators plotted on the maps, particularly sedimentation rates and progradation. A summarised interpretation of the development of Africa and Brazil over this period can be made as follows:

A. During the Late Cretaceous, centred on the Santonian (Figures 15 and 16), there was widespread uplift of the southern portion of Africa, extending as far north as Kenya in the east and along a narrow belt paralleling both the West African and Brazilian continental margins (Turner et al., 2008, Hackspacher et al., 2004, Morais Neto et al., 2008, Gallagher et al., 1998). These authors have noted similarities in the histories of these two margins, as is illustrated for AFTA based interpretations and for sediment progradational trends on Figures 3, 5.

North Africa remained flat and subject to frequent marine transgressions. The Late Cretaceous is the period of most rapid sedimentation over regions south of Angola and the present day Zambezi (Figure 6). Uplift, possibly slightly predating that for the South Atlantic margins, is inferred from sedimentation rates to affect the hinterland of the West African and Brazilian transform margins. Both transform margins suffered their highest offshore sedimentation rates at this time (Macgregor et al., 2003; Figures 6 and 7).

B. Much of this topography was worn down by the end of the Cretaceous on both continents, though it could have survived in the regions of highest uplift on the South African plateau, where sedimentation rates may have fallen due to climatic change. Other regions of Africa were subject to a warm, humid, non-seasonal climate during the Palaeocene and Eocene (Figures 13 and 14), resulting in frequent bauxite and laterite surfaces that represent the formation of the African peneplanation surface (Burke and Gunnell, 2008). North Africa and the northern part of Brazil remained flat and subject to frequent marine transgression, though uplift may have continued in SE Brazil, where the South American surface has been interpreted as being uplifted at this time (Tello et al., 2003), although P. Japsen (personal communication) considers it Oligocene in NE Brazil. Only one major African sedimentary thick is seen in the present-day Niger Delta, and this probably sourced sediment primarily out a palaeo-Benue system draining through the Central African rift system. The sediment starvation seen in most other margins suggests that there was a focus of river systems into the Benue region at this time.

C. The Afar Plume rose at the start of the Oligocene (Ebinger and Sleep, 1998; Figure 12), an event that seems to tie to an inflexion in average sedimentation rate across Africa that gradually increases thereafter to a peak at Present Day. The Afar Oligocene swell was probably accompanied by other swells in north-central Africa, which uplifted the African peneplanation surface at slightly different times (Burke and Gunnell, 2008). There is less indication of topographic change in the southern part of the continent (Partridge,1997), although this is disputed by Burke and Gunnell (2008) and in Brazil at this time. There was also a major climatic change at this time related to the glaciation of West Antarctica, with the formation of a major downcutting unconformity offshore at base Oligocene (Seranne, 1999). It is speculated that increased seasonality in global climates from Oligocene onwards probably also contributed to the rise in denudation and sedimentation rates.

D. The Miocene (Figure 11) saw an increase in the areal spread and amplitude of the swells. The Libyan swells, which are well dated from sedimentary thinning in surrounding basins, were active at this time. The elongate uplifts along the West African continental margin were reactivated, with a dating for initiation of uplift from unconformities offshore, salt movement and an increase in the erosiveness of offshore Burgalian channels (Walgenwitz et al., 1992). AFTA evidence and progradational trends in Brazil also support a model of accelerated denudation at this time, which is most easily related to a rejuvenation of topography (Cobbold et al., 2009), but is attributed to climatic change by Morais Neto et al. (2008). Periodic wetter climates in northern Africa resulted in short-lived pulses of sediment delivery and turbidite reservoirs to basins such as Mauritania (Vear, 2005). The nature and timing of uplifts in southern Africa at this time are unclear.

E. The latest Miocene (Figure 10) and Pliocene (Figure 8) saw the rise of the East African rift shoulders (Chorowitz, 2005), superimposed over earlier swells . The Pliocene also saw the reactivation of the Great Escarpment of Southern Africa, as evidenced by uplifted Pliocene marine strata (Partridge, 1997), the cessation of marine conditions and uplifted platforms in the onshore Kwanza Basin (Jackson and Hudec, 2005), and angular unconformities offshore Namibia. Sedimentation rates Africa-wide have built to a maximum in Recent times for river outlets tapping areas of renewed topography, with the notable exception of the margins to the South African plateau, despite the identification of a wet climatic phase in early Pliocene (M. de Witt, personal communication).

It is noted that uplifts, high topography, wet and seasonal climates, and lower sea levels are concentrated in the Late Cretaceous and Oligocene to Recent, this being reflected in a bimodal pattern on several aspects of African and Brazilian geology through time. Such bimodal patterns are observed in profiles of average sedimentation rates for the two South Atlantic margins and the East African margin (Figures 6 and 7), periods of AFTA-supported denudation (Figure 3), igneous intrusion ages, and periods of sediment progradation (Figure 5) on the continental margins. This bimodality is not seen in sedimentation rate patterns (Figure 6) for all regions; e.g., North Africa lacks any significant Cretaceous sediment input while Southern Africa lacks any significant Cenozoic sediment input. North African was not affected by the Cretaceous uplift phases, but explanations remain unclear why the Southern Africa sedimentation rate was so low throughout the Neogene. This could be explained by sustained aridity, but this interpretation conflicts with other evidence given above.

The changing topography since the Late Cretaceous has resulted in shifting drainage systems, with Africa's major river systems being of differing ages (Goudie, 2005). A major shift in drainage patterns, apparent in the Oligocene. Brazilian drainage systems, perhaps encountered less radical changes as the locations of the main highs remained constant; however, significant river captures are described by Karner and Driscoll (1999) and are shown on these maps.

Sedimentation Rates of Several Depocentres

As part of this study, the sedimentation rate profiles of several major depocentres were compared against temporal trends in the key indicators, and it was found that the sedimentation rate profiles can be seen to respond to tectonic and climatic changes identified in their drainage catchment areas (Figures 17, 18, 19, 20, and 21). Examples are shown of typical bimodal sedimentation rate profiles for the Congo and Campos basins (Figures 18 and 19), with Anka et al. (2009) documenting the two phases of fan development in the former. A now extinct Cretaceous system is illustrated by the Tano (Figure 20). The Zambezi, Orange, and Ogouee seem to have been the other major rivers in the Cretaceous, at a time at which many other African margins were sediment-starved. A drainage system not initiated until the Oligocene is illustrated by the Nile (Figure 20), which shows increases in sedimentation rate that tie to the main structural uplift phases documented in the Ethiopian sediment source area. The Niger (Figure 21) is an atypical system that was initiated in the Palaeocene (as the only major depocentre at that time) at the expense of a series of radial Cretaceous rivers (e.g., the Tano) that originally fed the transform margin (Macgregor et al., 2003). Figure 22 illustrates the importance of climatic control, showing a system in Mauritania that only delivered high sedimentation rates, a prograding sequence and delivery of turbidites to deepwater during a short-lived wet period (Vear, 2005). Final mention should be made of the Amazon profile (Figure 7), despite being the largest supplier of sediment in the study area at Present Day, this is geologically a very young river, initiated by the rise of the Andes in the mid-late Miocene.

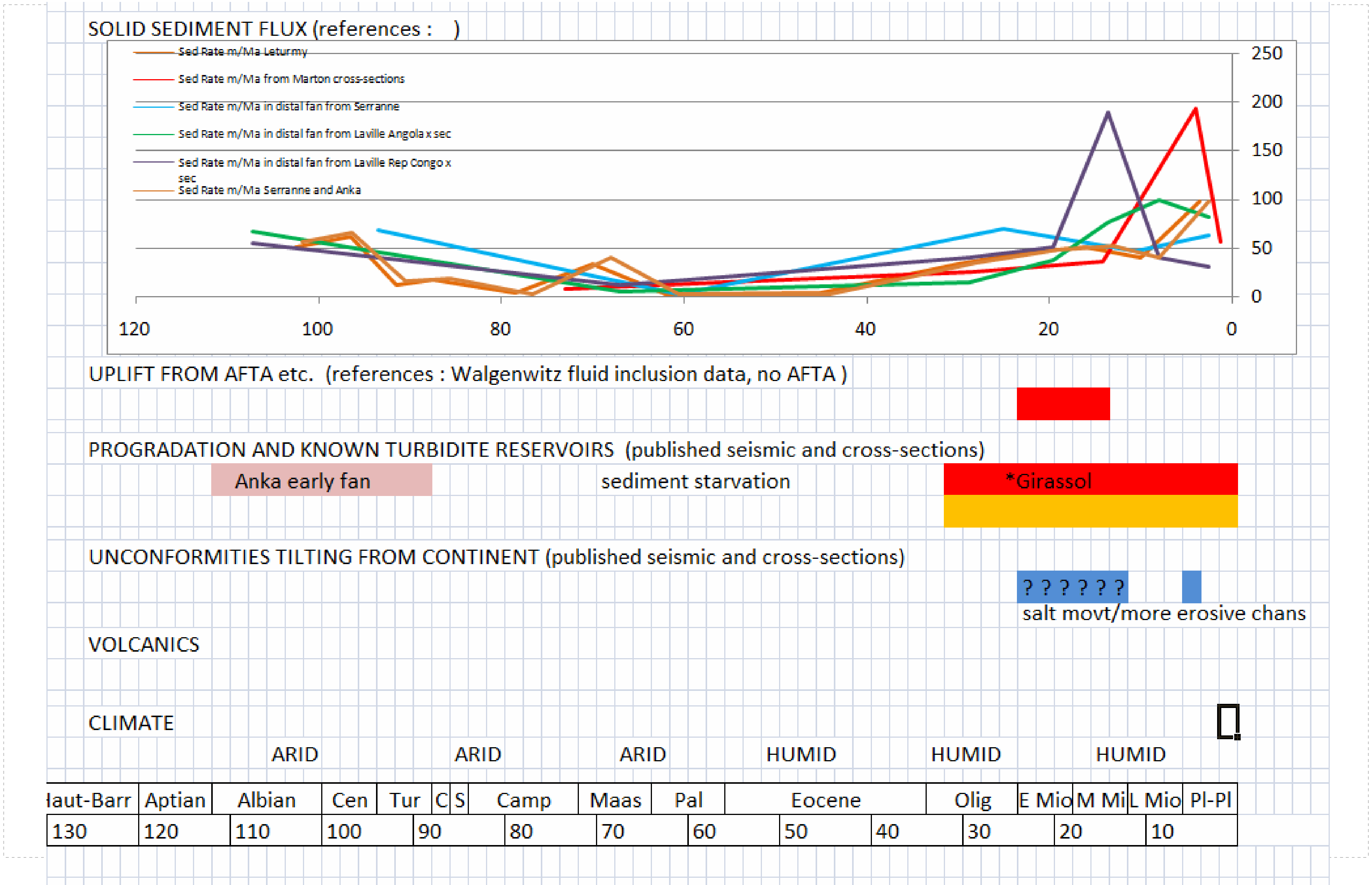

Figure 17. Congo Delta: Bimodal distribution of high sedimentation rates.

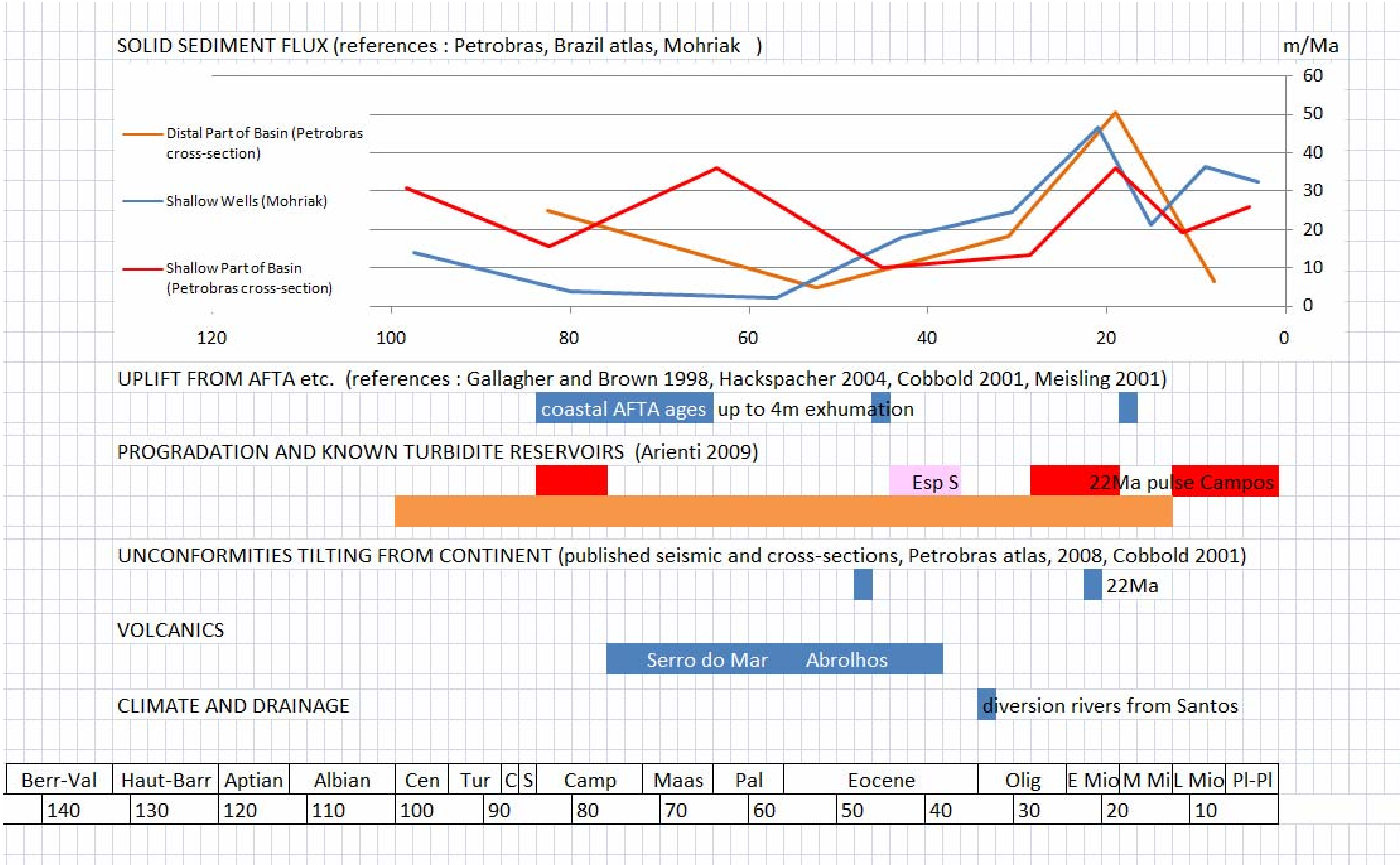

Figure 18. Campos Basin: Bimodal distribution of high sedimentation rates, significant sandy turbidite input at relatively low rates.

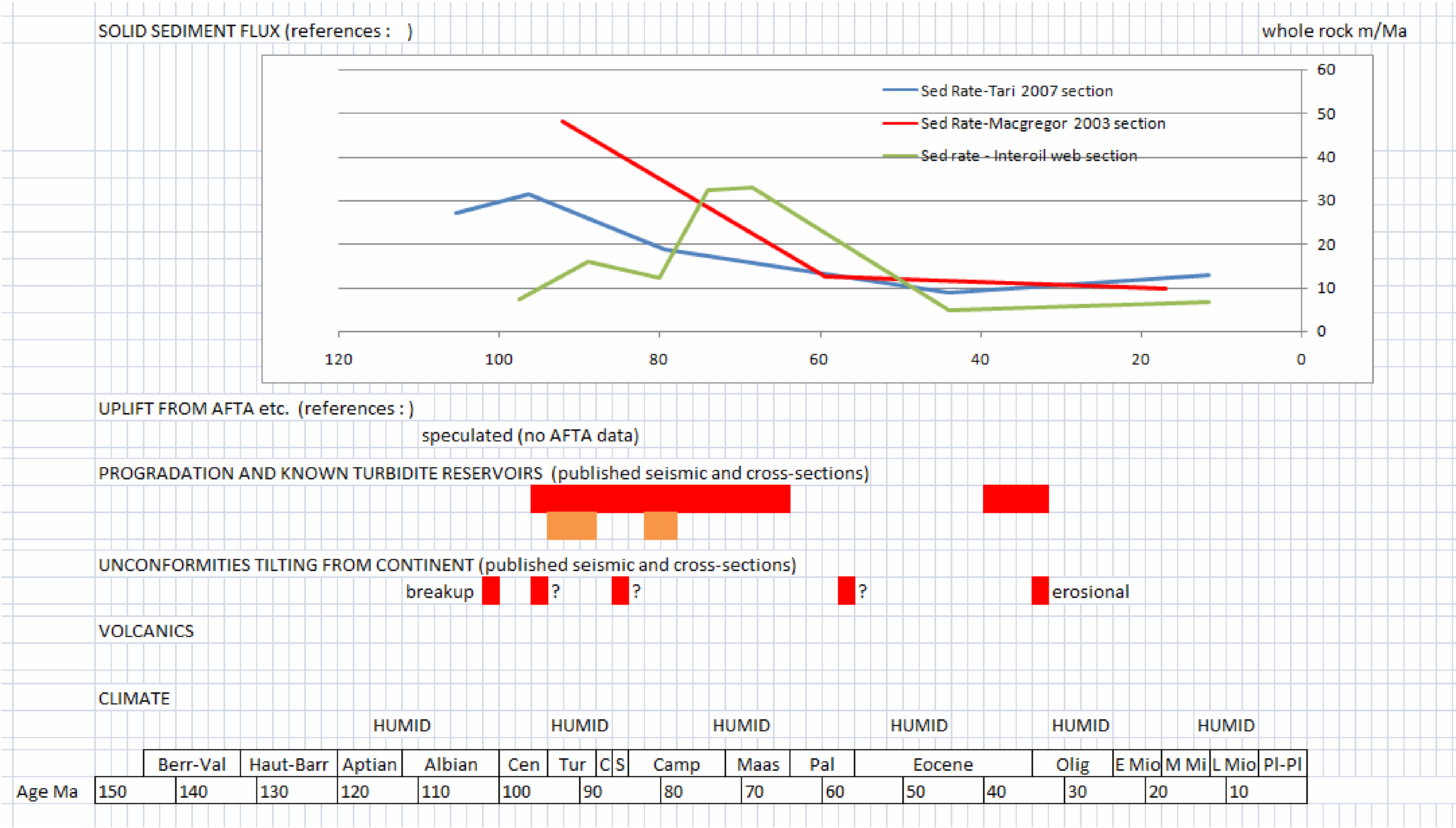

Figure 19. Ghana Tano Basin: High Cretaceous depositional rates only.

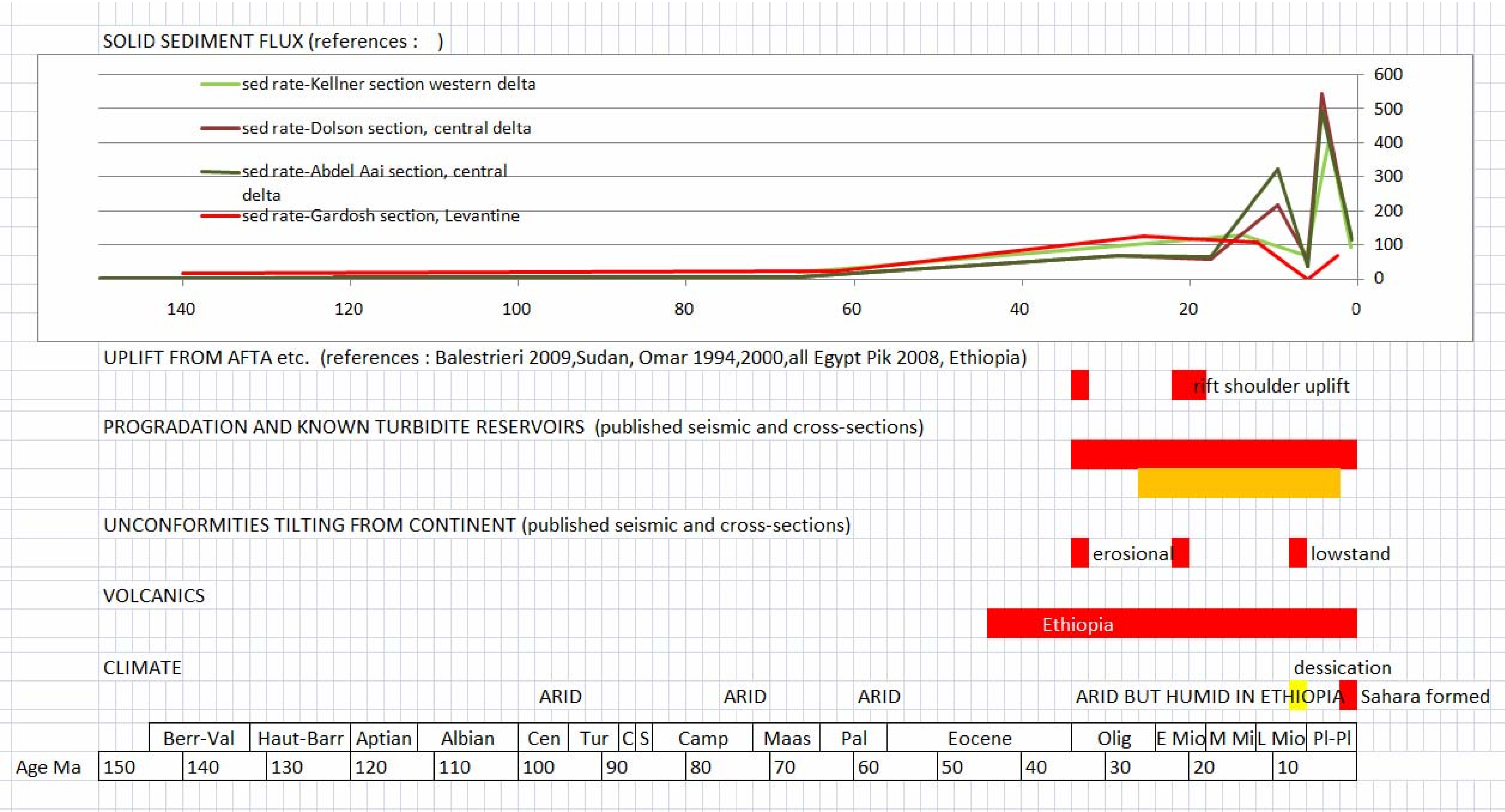

Figure 20. Nile: Oligocene to Recent high sedimentation rates only.

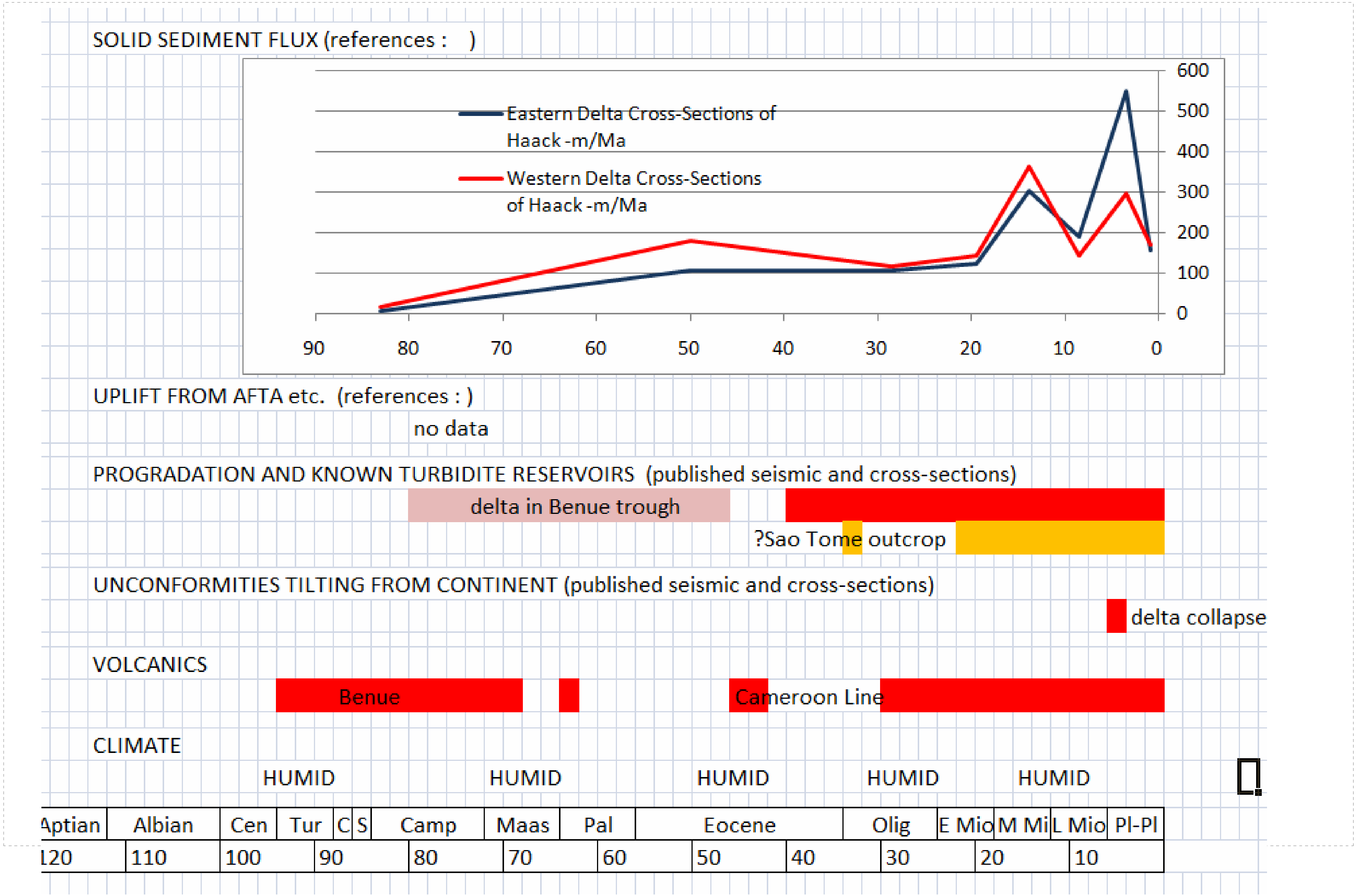

Figure 21. Niger Delta: Palaeocene to Recent high sedimentation rates.

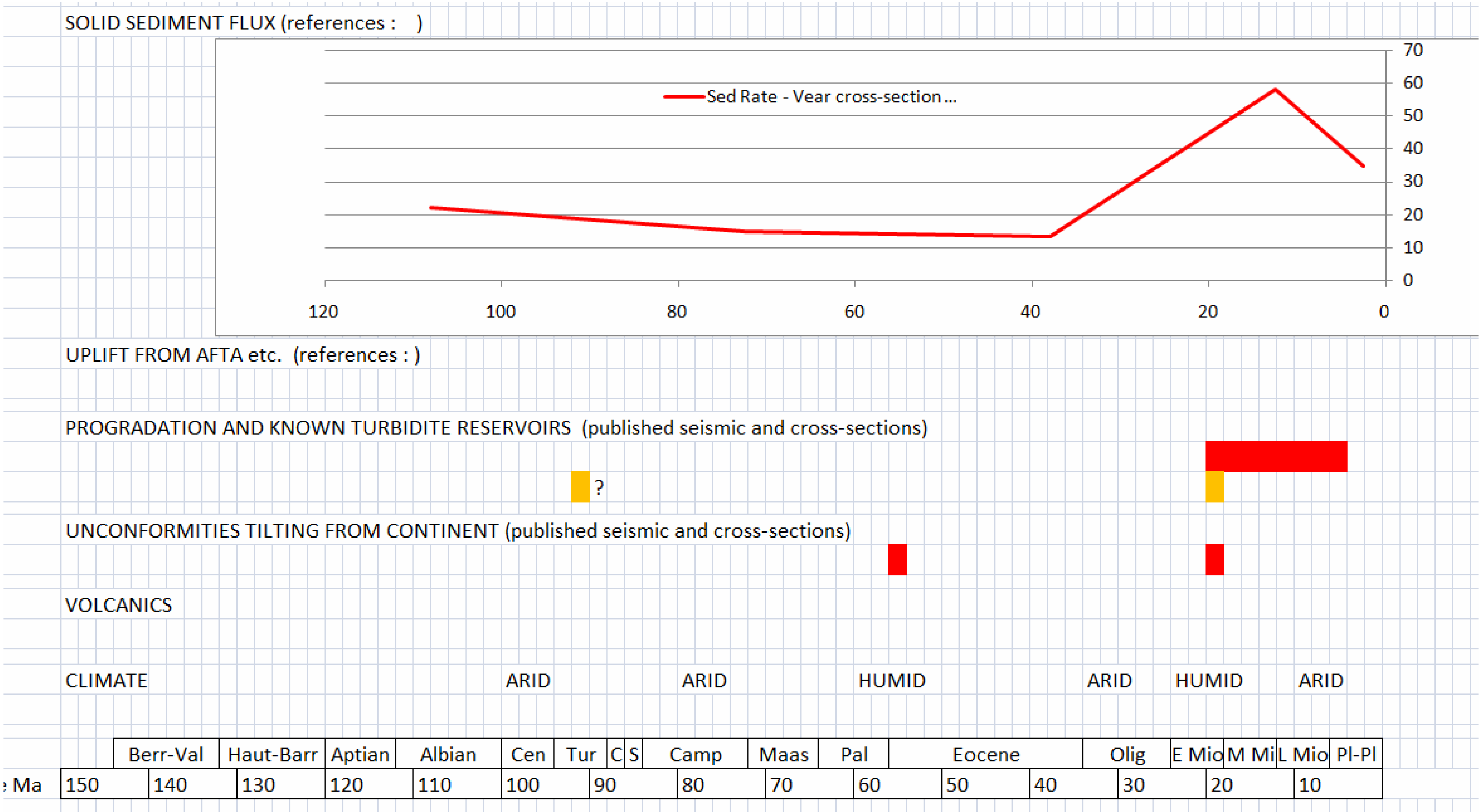

Figure 22. Mauritania: Short lived Miocene wet period with higher sedimentation rates.

Nature of Continental Uplifts

The shape, size, and age of the uplifts interpreted in this paper vary considerably, although with a general concentration in two geological phases. It is not possible to interpret these uplifts, the Atlas and East African rift shoulders excepted, as features consistent with conventional plate tectonics. Investigation of mantle-derived models require deep seismic imaging, as now is becoming available from the Africa-SPAN project (A.A. Nyblade, personal communication). While considerable further such data and analyses are required, it is possible to group the uplifts into four generic groups and to make some speculations on these:

a) Rift shoulders of the East African rift system (Chorowitz, 2005), which young in age from north to south (Figures 8, 10) , seemingly superimposed on:

b) Broadly circular uplifts ('swells') of Oligocene to Recent age, associated with alkali volcanism and attributed to upper mantle plumes (Ebinger and Sleep, 1998).

c) The very large uplift of the South African plateau, of primarily Cretaceous and probable ?late Neogene reactivation, which has limited associated igneous activity, limited to kimberlite pipes, and seems to overlie a lower mantle velocity anomaly (A.A. Nyblade, personal communication).

d) Elongate, mildly compressive uplifts, predominantly of Late Cretaceous and Neogene age, parallel to both the West African and Brazilian continental margins, again with limited associated igneous activity, for which some form of explanation must be sought (seemingly related to South Atlantic plate activity).

Implications for Petroleum Systems

Study of the occurrence of turbidite sand reservoirs and reserves through time also reveals the bimodality described above, with a rough cut-off of circa 20m/Ma sedimentation rate tying to the onset of significant sand input into deepwater, and a crude relationship observed between increasing sedimentation rate and reserves in known turbidite reservoirs thereafter (Figure 23). These high sedimentation rates are in turn tied to drainage catchments of regions of high uplift-related topography with wet climates. Sediment hinterland, lithologies being eroded, and steepness of continental slope also need to be considered here, as illustrated by the Campos Basin profile (Figure 18); despite relatively low sedimentary rates, thick turbidite sands are seen at several levels in the basin; these are probably indicative of a very sand-prone granitic hinterland. It is possible to predict from analyses of the main controls where the main prospective levels lie along the margins considered (Figure 24) and, in particular, to predict 'hidden' Cretaceous turbidite systems along 'fairways' extending from Guinea to Gabon, for example, and also along the Namibian margin. More detailed analysis for individual catchments, as portrayed in Figures 17-21, remains necessary to risk the occurrence of turbidite reservoirs for individual depocentres.

A further implication of this work is the realisation that source rocks in most onshore African basins with Cretaceous and older fills are generally not at their maximum burial or maturity (Burke et al., 2003). This opens up potential in many such onshore basins where maturity may have previously been underestimated on the basis of Present Day burial patterns. In such basins, it is often seen that vitrinite reflectance values are anomalously high at shallow levels or may be tilted/folded (e.g., Robert et al., 1990, for Lower Congo Basin; Tiesserenc et al., 1989, for Gabon). It may be useful in the future to characterise petroleum systems as generating pre- or post-African surface development. An attempt is made to do this on Figure 25, which is based on the published sedimentary columns and burial models made for each basin, with critical reference to the regional models developed in this paper.

Reserves >5000MMBOE		Campos (Olig)	Angola (Mio) Niger (Mio)	
Reserves 1000-5000 MMBOE		Campos (Sant-Maas, Eo) Ghana (Cen-Con) N Gabon (Sant-Maas)	Angola (Olig) Campos (Mio) Santos (Sant-Maas)	Niger (Plio)
Reserves 100-1000 MMBOE		Rio Muni (Sant-Maas) Santos (Eo, Olig)	Niger (E Mio)	
No Discoveries to date (examples)	Most Palaeogene sections in W Africa, Angola (Late K)		Niger (pre-Mio,Akata Sh) Liberia (Late K)	
	Sed Rate 0-20m/Ma	Sed Rate 20-50m/Ma	Sed Rate 50-300m/Ma	Sed Rate over 300m/Ma

Figure 23. Turbidite reserves vs sedimentation rate: Africa and Brazil.

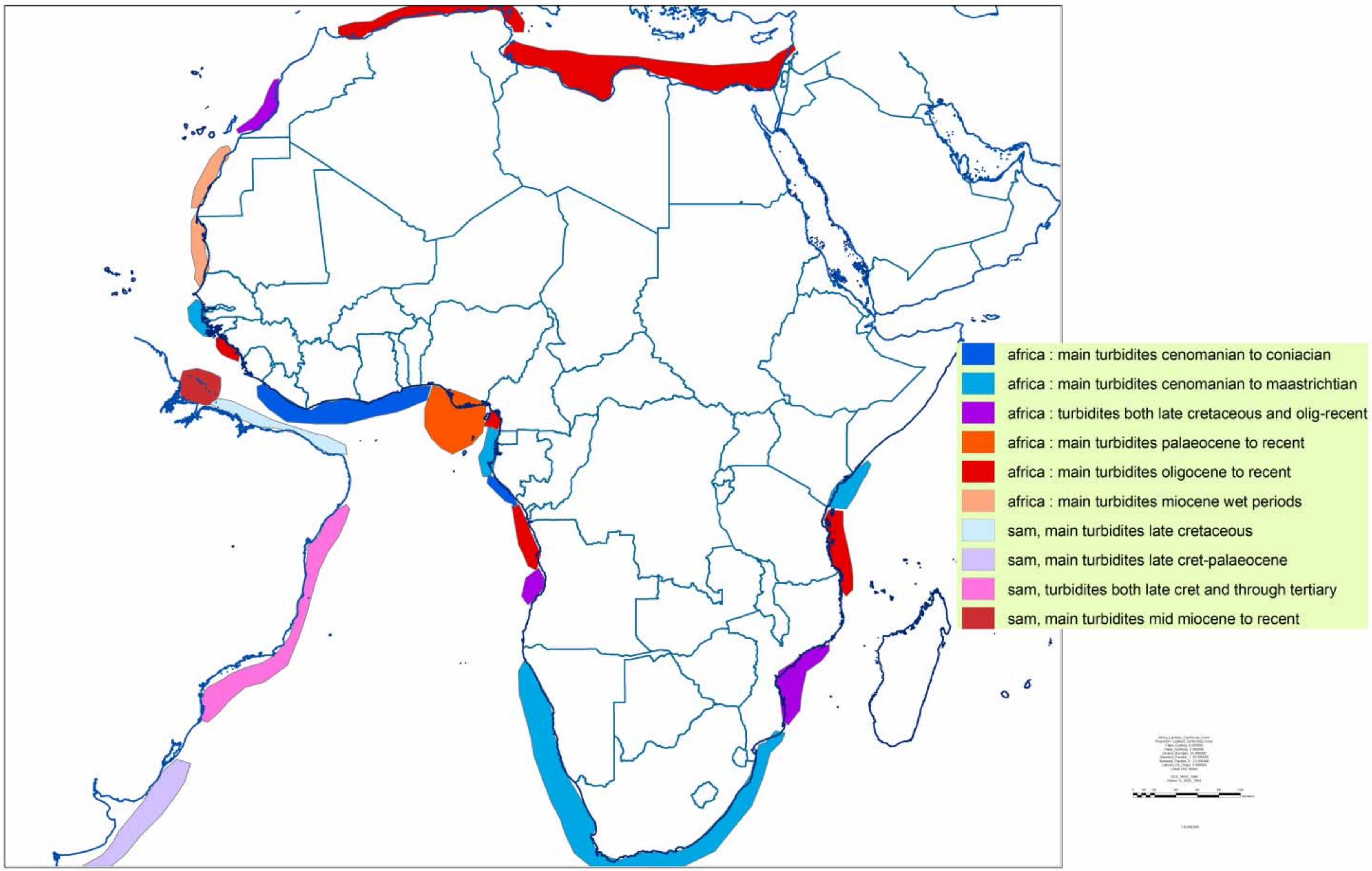

Figure 24. Interpreted ages of main turbidite plays on African and Brazilian margins.

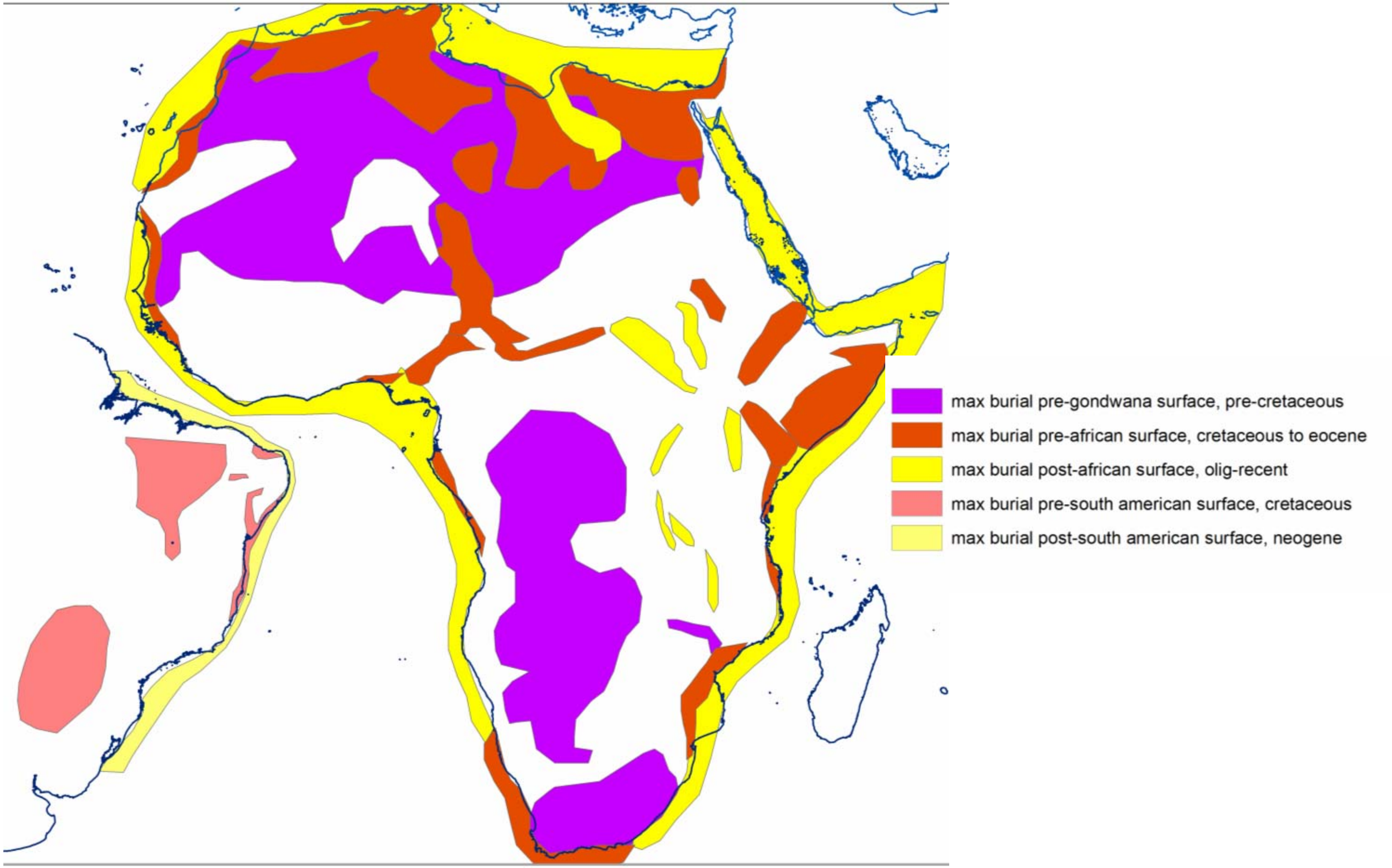

Figure 25. Age of maximum burial of source rocks relative to uplifted peneplanation surfaces.

Conclusions

1. Strong climatic and tectonic control is observed in this study on continental-margin sedimentation. Both wet (and/or seasonal) climates and a development of significant topography are required to give high denudation and sedimentary rates and a significant turbidite reservoir supply.

2. Two major phases of uplift are now identified in Africa, separated by a period of warm humid climate and low denudation rate in Palaeocene-Eocene times. This broad trend is reflected by bimodal distributions in many aspects of the geology (uplift, denudation, sedimentation rates, turbidite sand developments and reserves). More continuous uplift is observed in parts of the Brazilian margin, although even here there is evidence of the same bimodal patterns.

3. Individual depocentres and sedimentary rate and type can be understood or predicted through a systematic study of the key controls of climate and topography (uplift) in their catchment areas, as illustrated by the examples in this paper.

4. This work enables a mapping of turbidite fairways at different times.

5. Many onshore basins are not at maximum burial now, with generation prior to the uplift of the African surface and subsequent erosion. This perception increases potential kitchen areas in many basins.

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