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Cretaceous–Cenozoic sedimentary budgets of the Southern Mozambique Basin: Implications for uplift history of the South African Plateau

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ABSTRACT

In this study, data from 41 wells were used to quantify the evolution of the sedimentary budget in the Southern Mozambique passive margin basin, with a high temporal resolution for the Cenozoic period. We found that the drainage areas, which supplied sediments to the Southern Mozambique Basin, were eroded in two episodes. The first, of Mid–Late Cretaceous in age, is concordant with both thermochronological datation and sedimentary fluxes estimated by other studies in the Namibian and South African and Northern Mozambique margins. This erosion episode ended when the African surface, as defined by Burke and Gunnel (2008), had become flat and low-lying over most of the South African Plateau by ~65 Ma. Carbonate sediment deposition became more important in the shallow waters of the Mozambique basin after that time. The second erosion episode began at ~23 Ma and is likely due to an uplift event of the North-eastern part of the South African Plateau. It seems that the Limpopo catchment and the whole area sourcing the studied basin have inherited their present relief from two epeirogenic uplift pulses of Late Cretaceous and Miocene ages.

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1. Introduction

The Meso-Cenozoic history of the South African Plateau and its tectono-morphic evolution has been widely studied over recent decades. However, there remains no clear consensus on the timing of the related vertical motions, demonstrated by the existence of various models. These models fall into two broad categories, hypothesising either a continuous single phase of exhumation or multi-pulse exhumation. The timing of the uplift ranges between times prior to the Gondwana dispersion (Gilchrist et al., 1994; Van Der Beek et al., 2002; Pysklywec and Mitrovica, 1999; Doucoure and De Wit, 2003) and the Late Neogene (Partridge and Maud, 1987; Partridge, 1997). Significant stages of exhumation in the South African Plateau have been documented in the Late Cretaceous (King, 1967; De Wit et al., 1988; Brown et al., 1990, 2000; Gallagher and Brown, 1999; Tinker et al., 2008a,b; Kounov et al., 2009) and since the Oligocene (~30 Ma; Burke, 1996; Burke and Gunnell, 2008).

Erosion and subsequent sediment transport are commonly identified as results of the uplift of shields and plateaus (Stephenson, 1984; Bishop and Brown, 1992; Tinker et al., 2008b). Thus, the quantification of terrigeneous sediment in the surrounding marginal basins can be used to constrain the timing of continental relief evolution. Such an empirical approach has been used in the study of several basins located on the edges of the South African Plateau in Southern Africa (McMillan, 2003), including the Orange Delta basin (Guillocheau et al., 2012), the Outeniqua basin (Tinker et al., 2008b) and the Zambezi Delta off central Mozambique (Walford et al., 2005). However, except for Walford et al. (2005), these studies lack precision in the Cenozoic because they adopt a single time interval for the sediments accumulated during that epoch. As for the Limpopo delta and the associated Southern Mozambique Basin, which are the focus of this paper, the only published sediment estimates are based on a single interpreted seismic cross-section (Macgregor, 2010).

Here we aimed to unravel the vertical motion of the catchment area located at the north-eastern margin of the South African Plateau that supplies sediment to the Southern Mozambique Basin. Based on a compilation of 41 exploratory wells, we carried out a volumetric study of the sediments preserved in the Southern Mozambique Basin from the Early Cretaceous onwards. The presented results provide a better estimate of the uplift timing and the topographic building of the north-eastern margin of the South African Plateau relief.

2. Geological settings

The present-day Southern Mozambique Basin was formed during a complex geodynamic evolution of the south-east African

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margin (Fig. 1). Its formation started during the Karoo rift and the Karoo Magmatic events in the Triassic and Early to Middle Jurassic times, respectively. These events led to the Gondwanaland break-up in Late Jurassic–Early Cretaceous times and the subsequent drift of major- and micro-continents from the Early Cretaceous onwards (Martin and Hartnady, 1986; Salman and Abdula, 1995).

Also called the Mozambique Thinned Zone (Cox, 1992), the Southern Mozambique Basin is a thin Meso-proterozoic (or older) crustal fragment embedded within an oceanic crust of the Early Cretaceous age (Ben Avraham et al., 1995). Before the M10 magnetic anomaly marker of ~135 Ma, the prominent Dronning Maud Land of East Antarctica was adjacent to the Lebombo and the Mwenetzi monoclines (Fig. 1b). It subsequently slid southward for more than

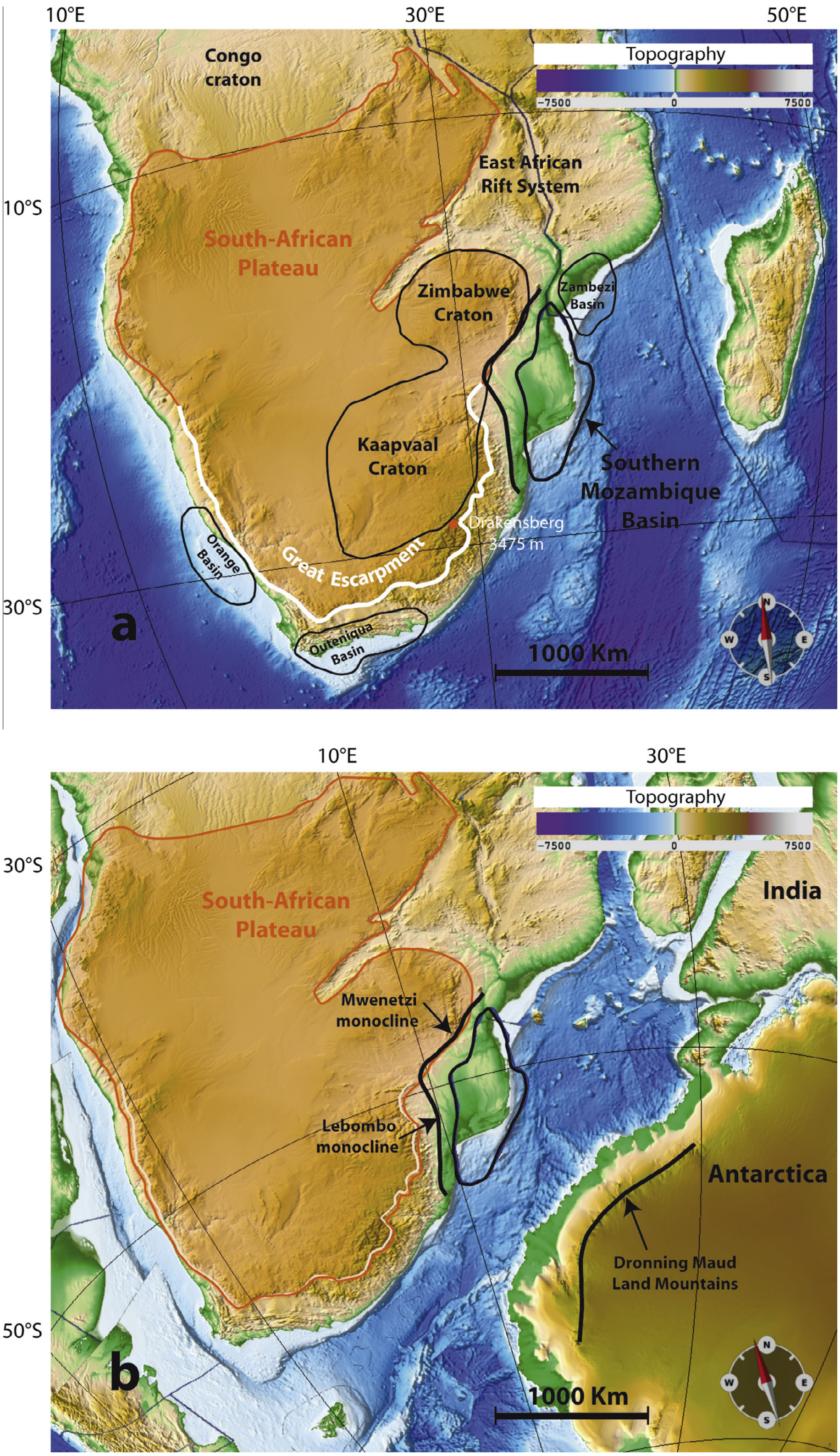

Fig. 1. Digital elevation model of Southern Africa. (a) Present day and (b) reconstructed at 150 Ma using the UTIG model (Lawver et al., 1998).

500 km along a transform fault east of the Lebombo monocline. The rifting occurred in the interval between the M21 and M10 magnetic anomalies ($\sim$150 to $\sim$135 Ma; Martin and Hartnady, 1986).

From Gondwana break-up to the present, several hundred thousand cubic kilometres of rock has been eroded from the South African continental relief and accumulated in the Southern Mozambique Basin and other passive marginal basins surrounding the South African Plateau (McMillan, 2003; Tinker et al., 2008a,b). The origins of these continental sediments have been related to the tectono-morphic and erosion processes experienced by the South African Plateau, the most dominant structure in Southern Africa (e.g., Guillocheau et al., 2012). This interior plateau, which today presents a flat relief at a high elevation (between 1000 and 1500 m), is separated from the coastal plain by the steeply-dipping Great Escarpment (Fig. 1). The plateau is a part of the African surface, which had probably been cut as a near sea-level peneplain and then uplifted and significantly eroded (Burke and Gunnell, 2008; Macgregor, 2010).

In the past 200 Ma, a total thickness of 2–7 km of rock, of which basalt was a major component, was eroded from the subcontinent's surface during two punctuated episodes of exhumation that occurred in the early-Cretaceous and mid-Cretaceous documented by Apatite Fission Track (AFT) and Apatite (U–Th–Sm)/He (or AHe) low-temperature thermochronology methods (Van Der Beek et al., 2002; Dauteuil et al., 2013; De Wit, 2007; Brown et al., 1990, 2000; Gallagher and Brown, 1999; Tinker et al., 2008a,b; Kounov et al., 2009; Flowers and Schoene, 2010). AFT and AHe data also describe a concordant radial pattern of rejuvenation from inland towards the Great Escarpment (Brown et al., 1990, 2000; Gallagher and Brown, 1999). In addition, another spatial distribution of low-thermal ages is observable, with a progressive decrease in ages of both the external and internal edges of the Great Escarpment from the Indian Ocean to the South Atlantic margins of South Africa (Gallagher and Brown, 1999). This distribution is correlated as a first approximation to the time delay ($\sim$30 Myr) in the Gondwanaland dislocation and associated rifting processes on both sides of the South African Plateau. A recent study by Braun et al. (2014) proposes a different hypothesis of plate tilting driven by the migration of the continent over a fixed source of mantle upwelling.

During the Cenozoic, exhumations and denudations along the South African Plateau are more problematic to detect by AFT and AHe data, as the vertical motions are not resolved by these methods. Nevertheless, the absence of completely reset AHe and annealed AFT ages constrains the maximum amount of Cenozoic denudation to less than 2 km (De Wit, 2007).

In addition, low rates for the present-day denudation in Southern Africa are estimated from cosmogenic nuclides analysis (Fleming et al., 1999; Cockburn et al., 2000; Brown et al., 2002; Kounov et al., 2007). These studies show denudation rates of 10–15 m/Myr and even as low as 1 m/Myr. Some researchers extrapolate low denudation rates across the entire Cenozoic on the basis of the prevailing aridity of the climate and the lack of substantial uplift throughout that period (Cockburn et al., 2000). However, other authors consider the Cenozoic as a principal period of uplift, topographic development and escarpment formation in southern Africa (Partridge and Maud, 1987; Partridge, 1997; Burke, 1996; Burke and Gunnell, 2008). Here we present evidence of an important Cenozoic sedimentary event and quantify the sediment volumes using a detailed time-scale for this period.

3. Data and methods

Located in the south-east corner of Southern Africa, the Southern Mozambique Basin is an area flanked on the west and the north-west by pre-Palaeozoic structures: the Kaapvaal and the Zimbabwe Cratons, respectively (Fig. 1a). The external limits of this basin are defined by the succession of the north–south Lebombo monocline and the north-east to south-west Mwenetzi monocline (Fig. 1b).

For the volumetric approach used in this study, boundaries of the Limpopo basin have been refined based both on geophysical (gravimetry) and geological (isopachs and structural features) data. The studied basin, presenting an area of approximately 25 million square kilometres, is limited to: the north by the thick sedimentary wedge of the Zambezi basin; the east by a set of north–south and north-east to south-west normal faults, which separate it from the distal part of the Zambezi delta; and to the west by the relatively high gravity structure corresponding to the Lebombo volcanic edifice (Fig. 2a). Presently, this basin is supplied by the Limpopo catchment and two other relatively small drainage basins (Save and Incomati) (Fig. 2b).

Data from 41 wells drilled in the Southern Mozambique passive margin basin were used to estimate the volume of sediment accumulated from Early Cretaceous to the present. To do so, we adopted a methodological approach that defines 9 time-intervals (Fig. 3) corresponding to different lithotectonic units or formations. These formations are often separated by unconformities, as reported in the stratigraphic log (Fig. 3).

The Cheringoma formation, deposited during the Middle to Late Eocene, is characterised by stacked nummulitic limestones with bands of clay and calcareous sandstone (Salman and Abdula, 1995). The maximal production was in the north and the south of the basin. In the central part, the carbonate production is probably inhibited by the terrigeneous input of fine-grain siliciclastics found in this part of the basin (Schlager, 2005), corresponding to the probable location of the main delta at this time period. Eastwards, the facies of the shallow-water shelf are replaced by deeper-water facies, which formed in conditions of a continental slope and continental rise (Salman and Abdula, 1995). In the Early and Middle Miocene, the environment was lagoonal with the deposition of the red dolomite of the Temane formation and the evaporites of the Inharrime formation. The overlying Late Miocene Jofane formation is characterised by marine carbonates: limestone, calcarenite and arenaceous limestone (Salman and Abdula, 1995).

To determine the evolution of the sedimentary flux and calculate changes in the sedimentation rate, the volume of sediment preserved in each formation was quantified using interpolation between the well data. The quantification of terrigenous sediment volumes requires two main corrections: a correction for carbonates produced *in situ*; and a correction for the sediment compaction exerted by the overlying sediment layers. A third potential correction is that for long-shore transport. Because the major break-up and seafloor formation period is complete by about 110 Ma (Lawver et al., 1998), we assume that, although we cannot presently quantify the effect of the long-shore transport, the rate of both sediment influx and removal would be approximately constant during our study and not affect the temporal pattern of sedimentation.

3.1. Compaction correction

The sediment decompaction was calculated based on the porosity–depth law in Allen and Allen (2013). This law assumes that density changes of a sedimentary unit are caused only by changes in the pore space (ignoring, for example, diagenesis) and that the porosity, ϕ (the ratio between pore space and sediment), is decreasing exponentially with the depth, z:

$$\phi(z) = \phi_0 \exp(-c \cdot z),$$

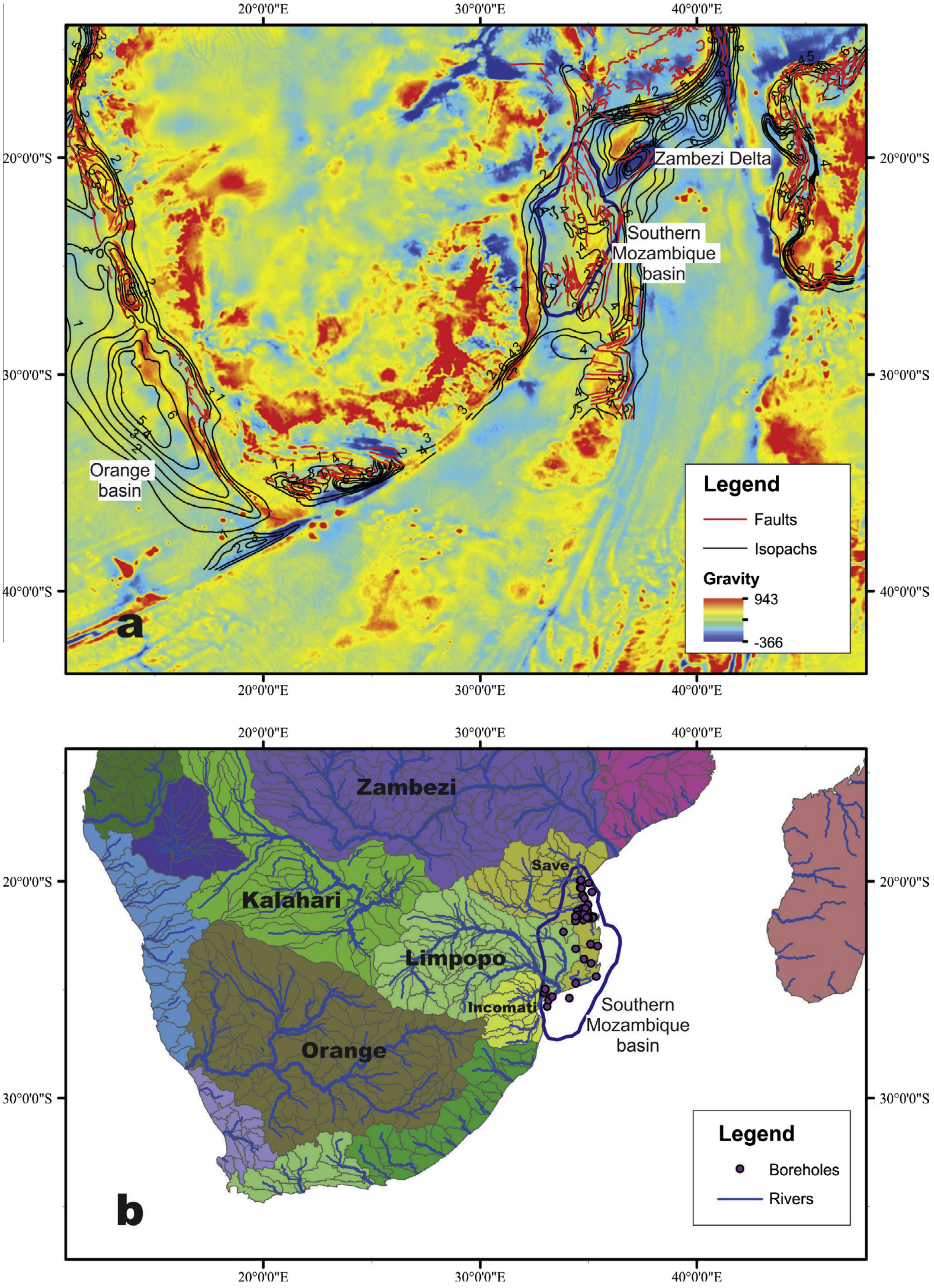

Fig. 2. (a) Map of sediment thicknesses, tectonic faults and gravity data of Southern Africa region. (b) Map of Southern African drainage system and major related drainage basins. Purple dots are location of the boreholes used in this study. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

where ϕ_0 is the porosity at the surface and c is a lithology-dependent coefficient that determines the slope of the porosity–depth curve. In the well-logs used in this study, the following lithologies are present: sandstone, shale, limestone and shaly sandstone. For each lithology, we used the ϕ_0 and c values as described by Sclater and Christie (1980).

The total pore volume of a sedimentary layer is given by integration over the depth interval:

$$\Delta z_{\text{pore}} = \int_{z_{\text{bottom}}}^{z_{\text{top}}} \phi_0 \exp(-c \cdot z)\mathrm{d}z = \frac{\phi_0}{c}\left[\exp(-c\,z_{\text{top}}) - \exp(-c\,z_{\text{bottom}})\right]$$

The decompacted thickness of a layer is its net thickness plus this depth-dependent pore volume. The decompacted thickness is determined by an iterative approach: decompacting a layer, removing it and then decompacting the layers beneath it.

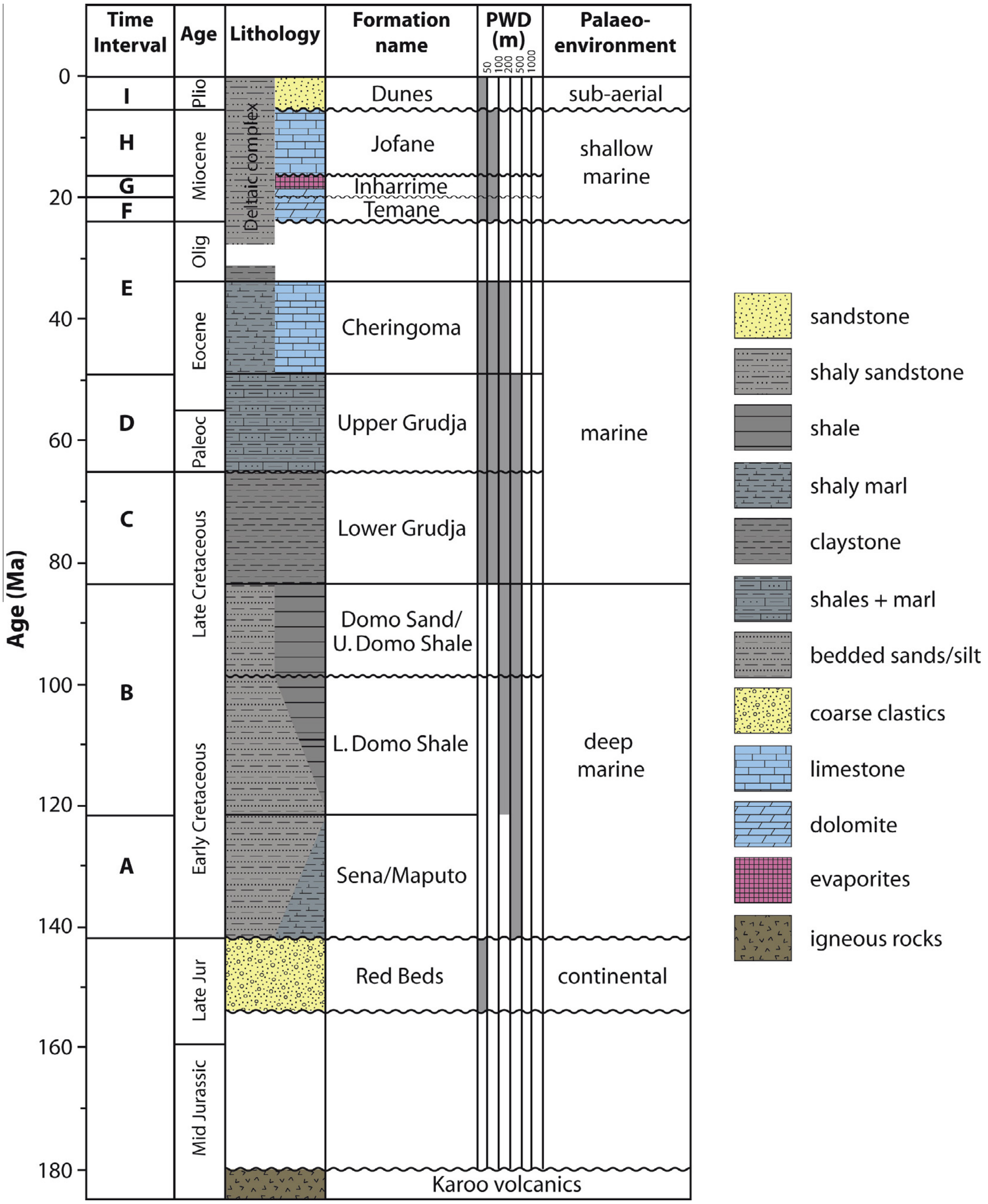

Fig. 3. Composite stratigraphic column of the Mozambique marginal Basin (modified after Salman and Abdula (1995)), with indication of the Palaeo-water depth (PWD) and the Palaeo-environment.

3.2. Carbonates correction

To calculate the terrigeneous sediment volume, the non-terrigeneous contribution is removed from the total sediment in the basin. In our case, carbonate deposits are the main non-terrigeneous sediments present and we assume all carbonates are produced *in situ*, given the shallow water depths associated with the carbonates in the well-logs. The thickness of carbonate layers for each time interval at each borehole were estimated based on information from the available well-logs. The well data was interpolated to a grid covering the region from 32°E to 37°E and from 19°S to 28°S at 0.01° resolution, excluding values outside the defined limits of the SMB. The interpolation is a two-stage process: first combining the well-data for each 0.2° block as a barycentric approach on a course grid with 0.2° grid spacing, using a weighted combination of the data from the nearest three available wells or boundary points. In the case of the sediment thickness, the thickness was assumed to be zero on the boundary and the barycentric interpolation included at most two boundary values. In the second stage, the course grid was refined to 0.01° resolution using a Delaunay triangulation.

4. Results

Grids of the carbonate content percentage and the non-terrigenous sediment thickness for each time interval are presented in Figs. 4 and 5.

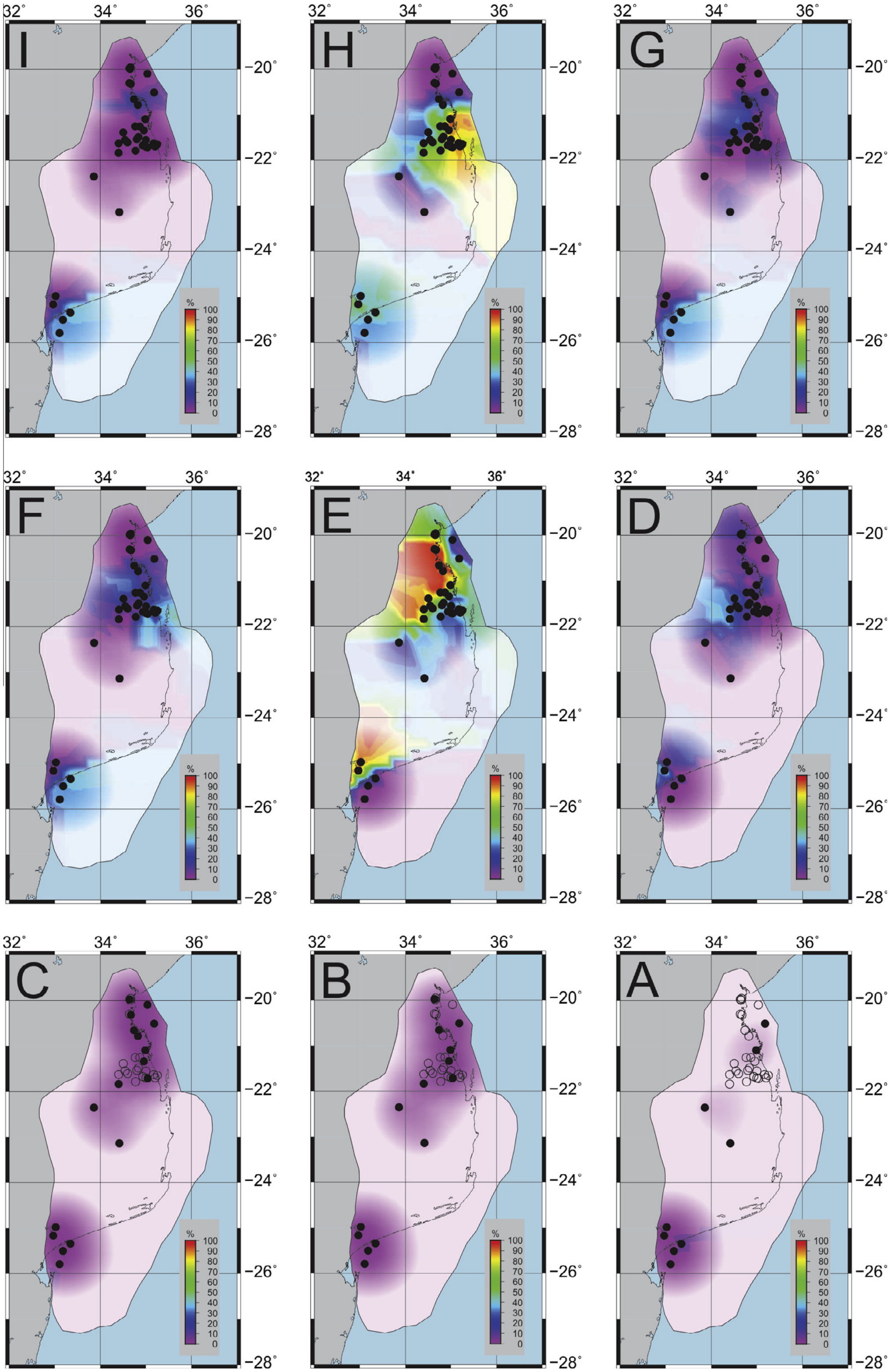

Fig. 4. Carbonate fraction maps for the Southern Mozambique Basin. (A) Earliest Cretaceous; (B) Mid-Cretaceous; (C) Latest Cretaceous; (D) Palaeocene–Early Eocene; (E) Middle Eocene–Oligocene; (F) Early Miocene; (G) Middle Miocene; (H) Late Miocene; and (I) Plio-Quaternary. White circle: not available data because the well is not reaching the series of that age; Black circle: available data from well. The transparency is indicating the uncertainty.

4.1. Carbonate deposits

For the Cretaceous (Fig. 4A–C), carbonate deposits are almost negligible, representing approximately 1% of the total sediment volume (Table 1). The Palaeocene and Early Eocene (Fig. 4D) represent a growth period for carbonates, which continued until the carbonate percentage peaked in the Middle Eocene to Oligocene (Fig. 4E), when 83% of the basin area was covered by carbonates and the maximum carbonate percentage increased to 38% of sediment volume (Table 1). In the wells available, the carbonates

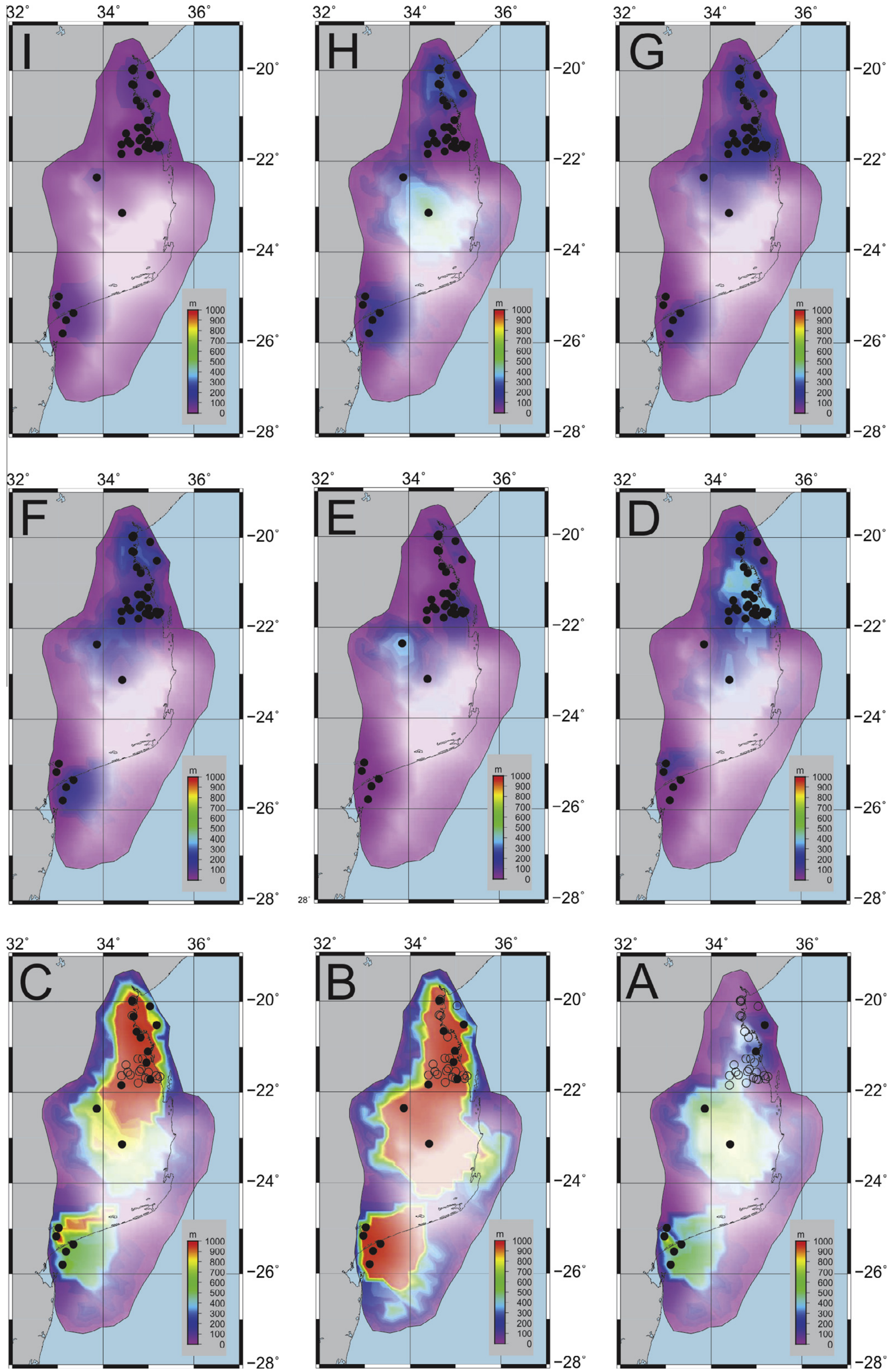

Fig. 5. Solid sediment thickness maps for the Southern Mozambique Basin. (A) Earliest Cretaceous; (B) Mid-Cretaceous; (C) Latest Cretaceous; (D) Palaeocene–Early Eocene; (E) Middle Eocene–Oligocene; (F) Early Miocene; (G) Middle Miocene; (H) Late Miocene; and (I) Plio-Quaternary. White circle: not available data because the well is not reaching the series of that age; Black circle: available data from well. The transparency is indicating the uncertainty.

are mostly concentrated landward of the present-day shoreline to the south and north of the Basin. In the Early and Middle Miocene (Fig. 4F and G) there is a small decrease in carbonates, with the main carbonate concentrations moving marginally seaward. In the Late Miocene (Fig. 4H), carbonates recover to cover much of the central part the basin and account for an average 38% of

Table 1
Detailing the carbonate distribution in the basin for the different time periods A–I.

Time period label	Mean percentage of carbonates (%)	% of basin area covered by carbonates
A	1	44
B	0	0
C	1	22
D	6	57
E	38	83
F	16	75
G	15	93
H	38	97
I	11	51

sediment volume (Table 1). Finally, in the Plio-Pleistocene (Fig. 4I), the carbonates retreat (except in the south of the basin), with a mean value of only 11% of total sediment volume (Table 1).

4.2. Solid sediment thickness

Few wells reach the earliest Cretaceous and therefore the distance between data is large, except in the south of the Southern Mozambique Basin (Fig. 5A). In the Mid-Cretaceous (Fig. 5B), the data coverage is only slightly better, but across the Basin, these wells report large amounts of sediment and the average sediment thickness is 728 m (Table 2). In the Late Cretaceous (Fig. 5C), there is a slight reduction of sediment supply to the Basin, with significant sediment found only along the centre of the northern segment of the Basin and the average sediment thickness dropping to 418 m (Table 2). In the Palaeocene and Early Eocene (period D), an almost equivalent age interval as compared with period C, the average sediment thickness drops to only 87 m. This low amount continues through the Middle Eocene and Oligocene (Fig. 5E), with 43 m deposited on average across 25.6 Myr, while the Middle Miocene has a similar sediment thickness deposited in only 7 Myr. Two sediment depocentres in the north of the basin are separated by a relatively low amount of sediment; in the south, up to 200 m of sediments were deposited in the zone off the present coast. The sediment volumes increase in the Late Miocene (Fig. 5H) with an average of 112 m deposited in 6.3 Myr (Table 2). However, in the Plio-Pleistocene very little sediment is deposited in the basin (Fig. 5I).

4.3. Sedimentary flux

Sediment volumes have been calculated by integrating the sediment thicknesses to the basin area. The ratio between volume of sediment and the time period required for its deposition yields to sedimentary flux. Sedimentary mass fluxes have been determined assuming an averaged sediment density of 2600 kg/m^3 and are presented in Fig. 6. The results show two periods of significant increase in sediment inputs into the Southern Mozambique Basin: the first period corresponds to the Mid–Late Cretaceous (Fig. 6B and C), during which the sedimentary flux was higher than 4.9×10^3 km^3/Myr with a maximum of 5.4×10^3 km^3/Myr obtained during the Mid-Cretaceous (Fig. 6B); the second peak was recorded in the Miocene. During the three Miocene time intervals (Fig. 6F–H), the sediment input was higher than 2.2×10^3 km^3/Myr, reaching a peak of $\sim 3.8 \times 10^3$ km^3/Myr in the Late Miocene. Compared to the Mid–Late Cretaceous, which lasted 46.5 Myr, the Miocene increase is only 17.7 Myr in duration (time periods F–H). However, the existence of the Oligocene unconformity means it is possible that the Neogene increase began earlier and was even more significant.

Table 2
Detailing the solid sediment thickness distribution and the sedimentation rate for the different time periods A–I.

Time period label	Mean thickness of sediments (m)	Average sedimentation rate (m/Myr)
A	221	6.6
B	728	27.3
C	418	23.4
D	87	5.1
E	43	1.7
F	72	10.3
G	63	14.3
H	112	17.8
I	20	3.8

These two periods of high sedimentation rates are followed by two periods of low sediment input, firstly from the Palaeocene to the Oligocene (Fig. 6D and E) and secondly during the Plio-Pleistocene (Fig. 6I). During these periods of sediment starvation, the flux of terrigeneous inputs never exceeded $\sim 1.1 \times 10^3$ km^3/Myr and reached its minimum value in the Middle Eocene–Oligocene.

5. Discussion

A major shift in drainage affected south-eastern Africa (including the study area) during the Late Cretaceous–earliest Palaeocene (Moore and Larkin, 2001; Haddon and McCarthy, 2005; Goudie, 2005). This was associated with intracratonic subsidence and formation of the internally drained Kalahari Basin, as well as flexural uplift along the Indian Ocean margin, leading to beheading of the upper tributaries of the Limpopo River. As a result, the size of the drainage basin supplying sediment into the Mozambique area, including the Southern Mozambique Basin, decreased significantly (Fig. 6).

There have been a number of arguments posited towards a Late Cenozoic phase of uplift of the South African Plateau, an idea also supported by our results. Alternative explanations from either eustatic sea-level or regional climate change are unlikely because the early Miocene was a time of slight sea-level rise (Haq et al., 1987) and lithological indicators are that the regional climate was relatively stable during the Oligocene–Miocene transition (Scotese and Moore, 2011).

In addition, two incised valley generations (King, 1967) of the South African Plateau indicate two periods of uplift since its formation in the Late Cretaceous. The inland presence of Eocene marine deposits at an altitude of 400 m at Need's Camp, South Africa (Partridge and Maud, 1987), further supports the hypothesis of post-Eocene uplift of Southern Africa. In addition, numerical modelling of the thermal histories of the oil wells in the Southern Mozambique Basin also requires significant uplift and erosion at ca. 25 Ma in order to achieve an acceptable calibration of the model to the available maturity data (Matthews et al., 2001). These results agree well with our results of increased Miocene sedimentation (Fig. 6).

The sedimentary fluxes from Fig. 6 are placed, for comparison, alongside results from other studies in the basins surrounding the South African Plateau (Fig. 7). Studies in the Orange delta and the Outeniqua basin do not show any variation in the sedimentary flux during the Cenozoic because of their low temporal resolution for that period. Our study and the study by Walford et al. (2005) in the Zambezi delta show sediment pulses higher than 3×10^3 km^3/Myr in the Late Cenozoic. In the Zambezi delta, high sedimentation rates have been recorded since the Oligocene. However, given the Oligocene's major unconformity, there exists the potential that a significant volume of sediments in the Late Oligocene may have been removed and redistributed outside the

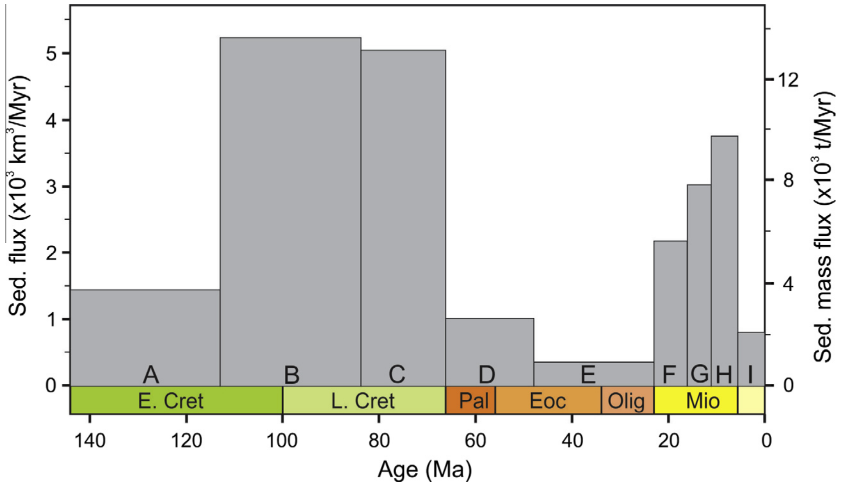

Fig. 6. Variation of the solid sediment flux deposited through the time in the Southern Mozambique Basin. Flux is expressed in terms of volume (km^3/Myr; left-hand axis) and in terms of mass (t/Myr, assuming an averaged sediment grain density of 2600 kg/m^3; right-hand axis).

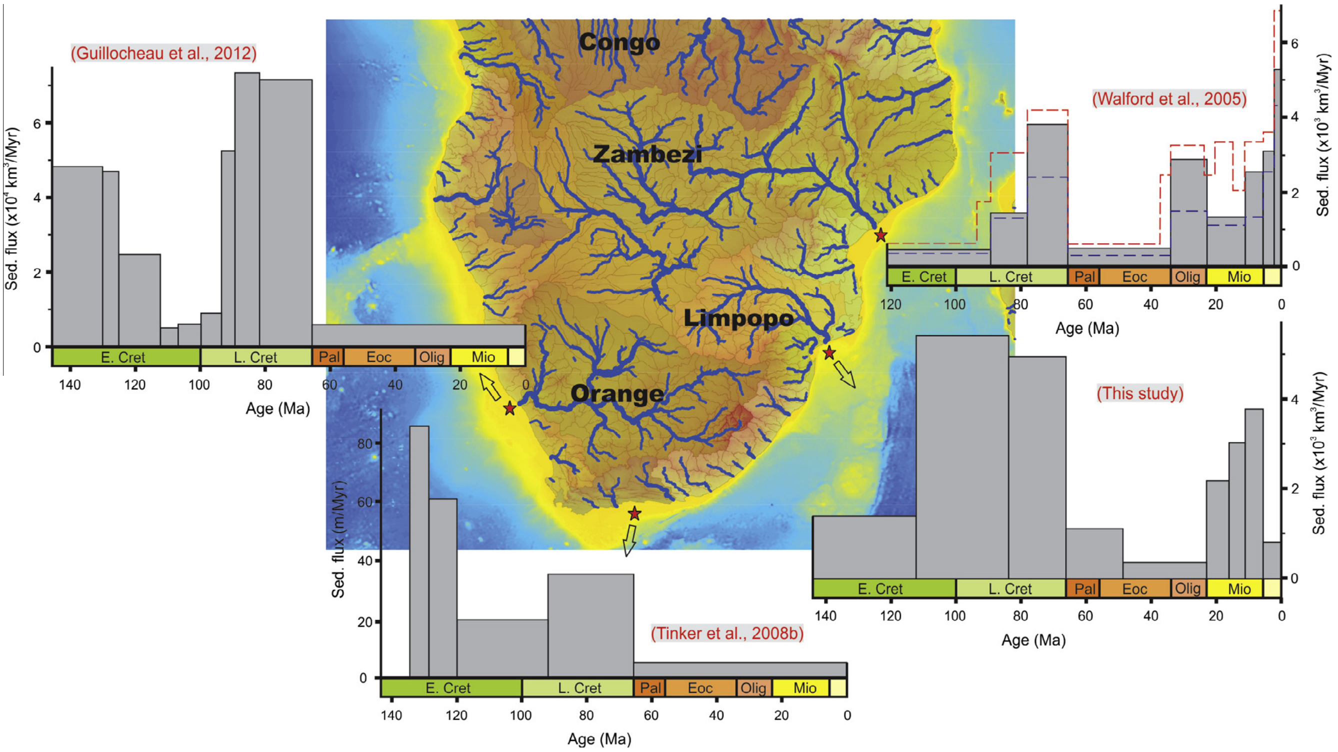

Fig. 7. Comparison between sedimentary fluxes in the surrounding margins of the South African Plateau: the Orange delta (Guillocheau et al., 2012), the Outeniqua basin (Tinker et al., 2008b), the Limpopo delta (this study), and the Zambezi delta (Walford et al., 2005). Note that the sedimentation rate in the Outeniqua basin is expressed in m/Myr and not in km^3/Myr like in the other cases.

boundaries of the Southern Mozambique Basin. Indeed, the Oligocene interval is thin or missing in many marginal basins around Africa (Jackson et al., 2005).

The reasons for the uplift episodes of the South African Plateau are less clear, but may be related to epeirogenic uplift associated with an increase in mantle buoyancy (Flowers and Schoene, 2010). The first Mid–Late Cretaceous event overlaps in age with the Kimberlite intrusions across the southern African hinterland (>450 kimberlites, dated between 90 and 100 Ma, Jelsma et al., 2004, 2009) and with the formation of the Agulhas Falkland LIP (90–100 Ma) along the south coast of Southern Africa (Tinker et al., 2008a). However, because tectonic uplift and volcanic activity are not always linked, the lack of any significant igneous activity across the South African Plateau during the Miocene does not refute the occurrence of an uplift event during that time period.

6. Conclusions

Here we used abundant well data to quantify the evolution of the sedimentary budgets in the Southern Mozambique Basin in order to unravel the uplift timing of the South African Plateau. We achieved a higher temporal resolution for the Cenozoic period than previous studies analysing the marginal basins surrounding the South African Plateau. Our data identify two major periods of high sedimentation rates. The first, of Mid–Late Cretaceous age, is concordant with thermochronological datation and with sedimentary budgets estimated by other studies in the Orange, Outeniqua and Zambezi basins, where similar high accumulation rates have been documented. The second event is Miocene in age and yields important sedimentation rates close to those recorded in the Mid–Late Cretaceous. In the absence of climatic change and eustatic sea-level fall during the Oligocene–Miocene transition, the Miocene peak of sedimentation in the Southern Mozambique Basin can only be the consequence of a significant uplift that occurred in the area sourcing this basin. Based on our findings, it seems more likely that at least the North-eastern part of the South African Plateau has inherited its present relief from two epeirogenic uplift pulses of Late Cretaceous and Miocene ages.

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