A Mid Cretaceous paleo-Karoo River valley across the Knersvlakte plain (northwestern coast of South Africa): Evidence from apatite fission-track analysis

A. Kounov
Institute of Geology and Palaeontology, Basel University, 4056 Basel, Switzerland
email: a.kounov@unibas.ch

G. Viola
Geological Survey of Norway, 7491 Trondheim, Norway
email: giulio.viola@ngu.no

M.J. de Wit
AEON and Department of Geological Sciences, University of Cape Town, 7701 Rondebosch, South Africa
email: maarten@cigces.uct.ac.za

M. Andreoli
South African Nuclear Energy Corporation, PO Box 582, 0001 Pretoria, South Africa; School of Geosciences, University of the Witwatersrand, P Bag 3, 2050 Wits, South Africa
email: marco@necsa.co.za

ABSTRACT

Apatite fission track analysis of gneiss samples across the Knersvlakte plain in the coastal area of western South Africa reveals the existence of a relatively deeply incised paleovalley flanked by high ridges formed during the Mid Cretaceous. This paleovalley coincides with the present course of the Krom River through the Great Escarpment.

Modelling of the fission-track data suggests that the main stage of intense channel erosion, triggered by uplift of the catchment area, occurred between ~120 and ~110 Ma and was followed by a period of progressive hillslope erosion and interfluve degradation. It is suggested that the paleo-Karoo River and its tributaries were responsible for the formation of this relief. The present-day lower relief formed by continuing erosion starting at ~90 Ma, time when all the analysed samples had already been exhumed to a depth corresponding to temperatures below 60°C (~2 to 3 km).

Introduction

The list of studies dealing with the geomorphological evolution of the southwestern margin of the African continent is long and distinguished (*e.g.* Suess, 1904; Penck, 1908; du Toit, 1926; King, 1951, 1953; Ollier, 1985; Partridge and Maud, 1987; Gilchrist and Summerfield, 1990). Several significantly different models have been suggested for its morphotectonic development based essentially on direct geomorphological observations and large-scale correlations of erosional surfaces (*e.g.* du Toit, 1926; King, 1951; Ollier, 1985; Partridge and Maud, 1987; Gilchrist and Summerfield, 1990; Partridge, 1998; Brandt *et al.,* 2005). Recently, low-temperature thermochronological studies have added important constraints to the understanding of the timing and modes of landscape evolution in this region, which is characterized by a rough low-lying coastal plain, a seaward-facing escarpment and an elevated inland plateau (*e.g.* Fleming *et al.*, 1999; Cockburn *et al.,* 2000; Brown *et al.,* 2000; Van der Wateren and Dunai, 2001; Brown *et al.,* 2002; Tinker, 2005; Kounov *et al.,* 2007; Tinker *et al.,* 2008a, b; Kounov *et al.,* in press). In detail, these data, together with numerical models of surface evolution (*e.g.* van der Beek and Braun, 1999; Gilchrist *et al.,* 1994), have contributed to new models of margin evolution, where the initial location of the present escarpment was probably controlled by a major inland topographic divide separating a low-gradient interior drainage from the higher-gradient river systems flowing towards the rapidly changing base level at the oceanic margin (Cockburn *et al.,* 2000; Brown *et al.,* 2002). Therefore, the escarpment, may have originated only a few kilometres oceanward from its present position.

These recent advances notwithstanding, two issues concerning the geomorphological evolution of the west coast of South Africa still remain unresolved:

1. What are the mechanisms and processes that generated the remarkable present-day topographic relief and when did this happen?
2. How did drainage systems evolve in response to relief evolution?

Syn- to post-Gondwana break-up evolution of southern Africa has been related to dynamic processes in the mantle (*e.g.* Burke, 1996; Andreoli *et al.*, 1996; Doucouré and de Wit, 2003; de Wit, 2007; Tinker *et al.,* 2008a; Kounov *et al.,* in press), but the timing of these processes is disputed. Some authors consider that the main geomorphological features of southern Africa are

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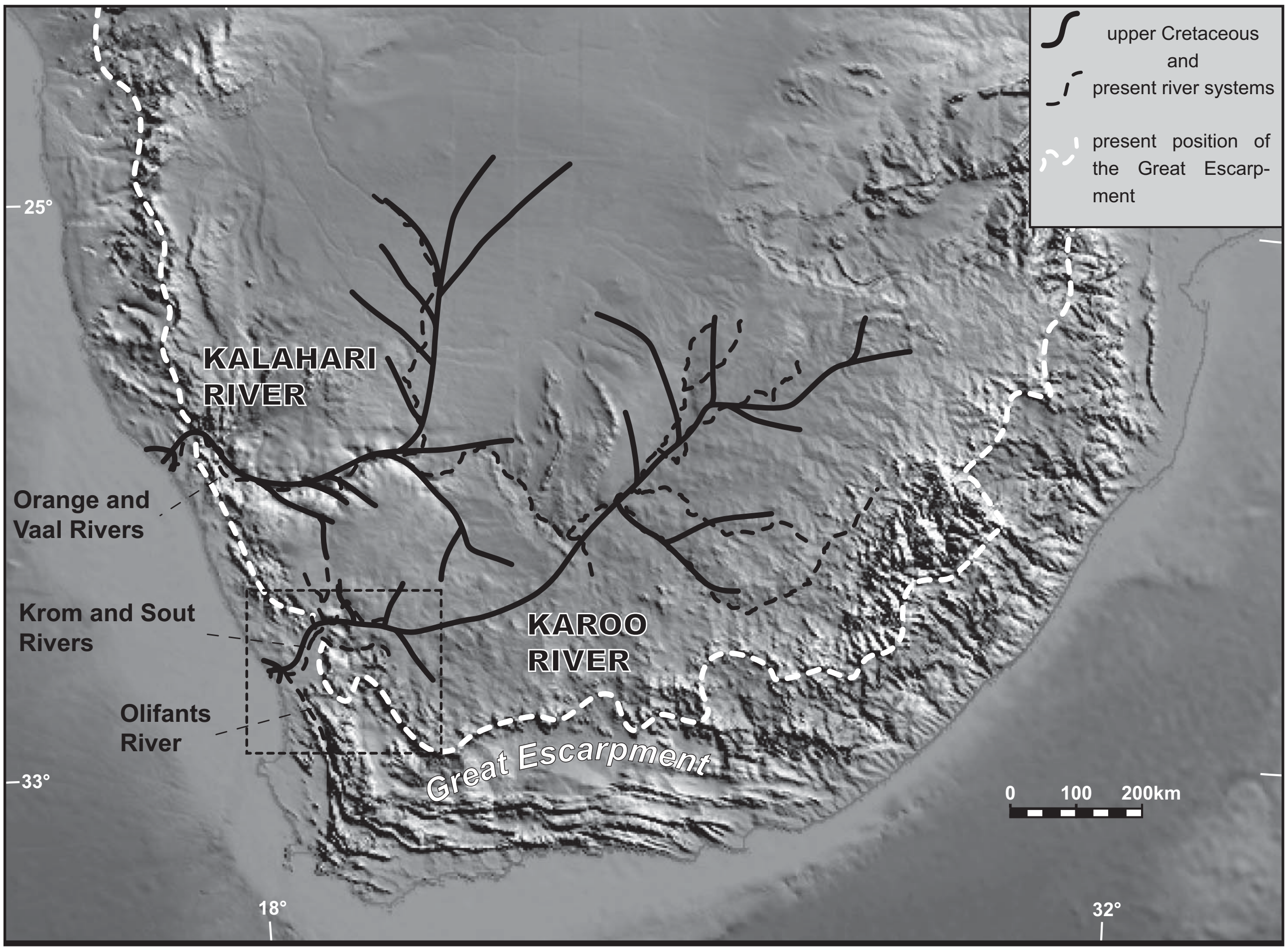

Figure 1. Shaded relief map of Southern Africa showing the reconstructed Upper Cretaceous drainage system of the Kalahari and Karoo rivers and the present systems of the Orange, Krom and Olifants rivers (modified after de Wit, 1993; Partridge, 1989 and de Wit *et al.*, 2000). The box indicates the location of the area covered by the map shown in Figure 2. The white dashed line represents the present-day position of the Great Escarpment.

predominantly Cenozoic in age (possibly as young as 30 Ma, Dingle *et al.*, 1983; Burke, 1996; Partridge 1998; Moore and Blenkinsop, 2006). Other researchers, however, suggest that much of the present-day topography had already formed during the Cretaceous (King, 1951; de Wit *et al.*, 1988; Brown *et al.*, 1990, 2000; de Wit *et al.*, 2000; Doucouré and de Wit, 2003; de Wit, 2007; Kounov *et al.,* 2007; Tinker *et al.,* 2008a; b; Kounov *et al.,* in press).

Regarding the evolution of the river systems draining the southernmost part of the African continent, it is generally acknowledged that two major, generally southwest- to west-flowing river systems drained most of the interior of southern Africa since the Cretaceous, the Kalahari and Karoo river systems (Figure 1; *e.g.* Dingle and Hendey, 1984; Malherbe *et al.*, 1986; Partridge and Maud, 1987, de Wit, 1993; Partridge, 1998; de Wit *et al.*, 2000). The northernmost Kalahari River drained the Kalahari region and entered the Atlantic Ocean approximately where the mouth of the Orange River is presently located (Figure 1).

M.C.J. de Wit (de Wit, 1993; de Wit *et al.,* 2000) suggested, on the basis of sedimentological evidence, that the middle and lower courses of the present-day Orange River were formerly located up to 200 km south of their present position, and formed what he named the Karoo River. This paleo-system probably entered the sea near the present mouth of the Olifants River and may account for the abundant alluvial diamonds in the offshore marine deposits (Figure 1). Different opinions exist, however, on the evolution of the Karoo River drainage system and the time when it was initiated. Some propose that this Karoo River existed already during the Cretaceous, and that it was captured during the Paleogene by the Kalahari River (*e.g.* Partridge and Maud, 1987; de Wit, 1993; Partridge, 1998; de Wit *et al.*, 2000). Others instead suggest that the Karoo River was established only in the Paleogene and existed until the Neogene (*e.g.* Dingle and Hendey, 1984).

If the Karoo River drained into the Atlantic during the Cretaceous, then it should have left a marked drainage feature/network across the escarpment, for example, in the form of a significant eroded valley, particularly if models that advocate Cretaceous development of the Great Escarpment flanking the west coast of South Africa are correct.

Here, we set out to test these two different age-models of the Karoo River evolution by using low

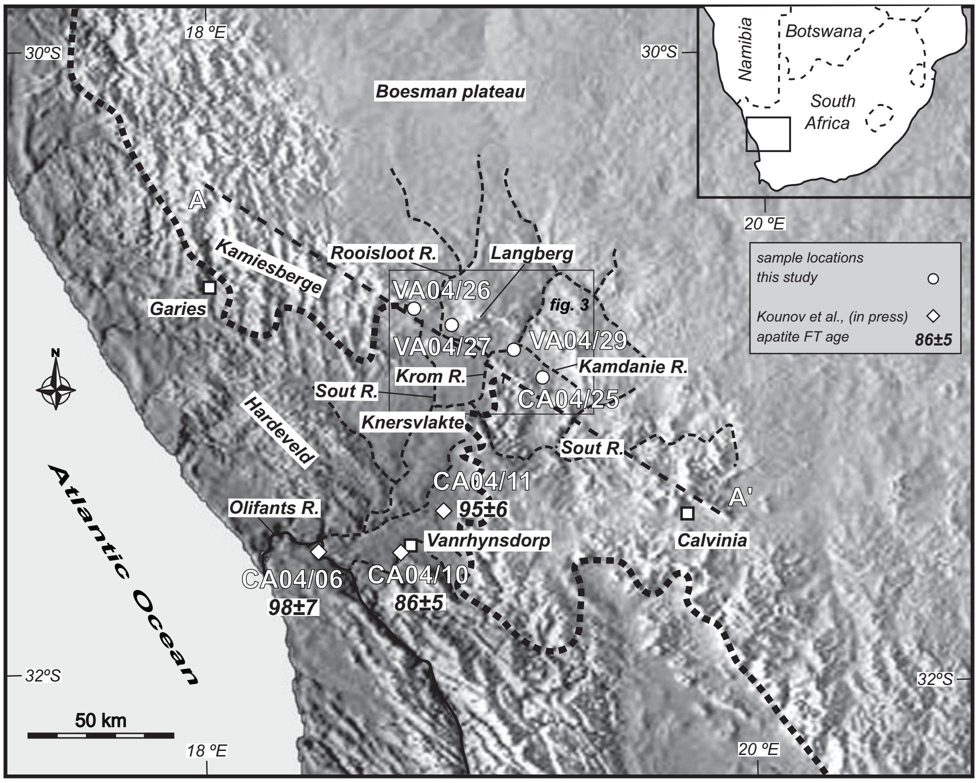

Figure 2. Shaded relief map of the study area (western South Africa). Line AA' traces the section of Figure 4. The box frames the area shown in Figure 3. The thick black dashed line shows the present-day position of the Great Escarpment.

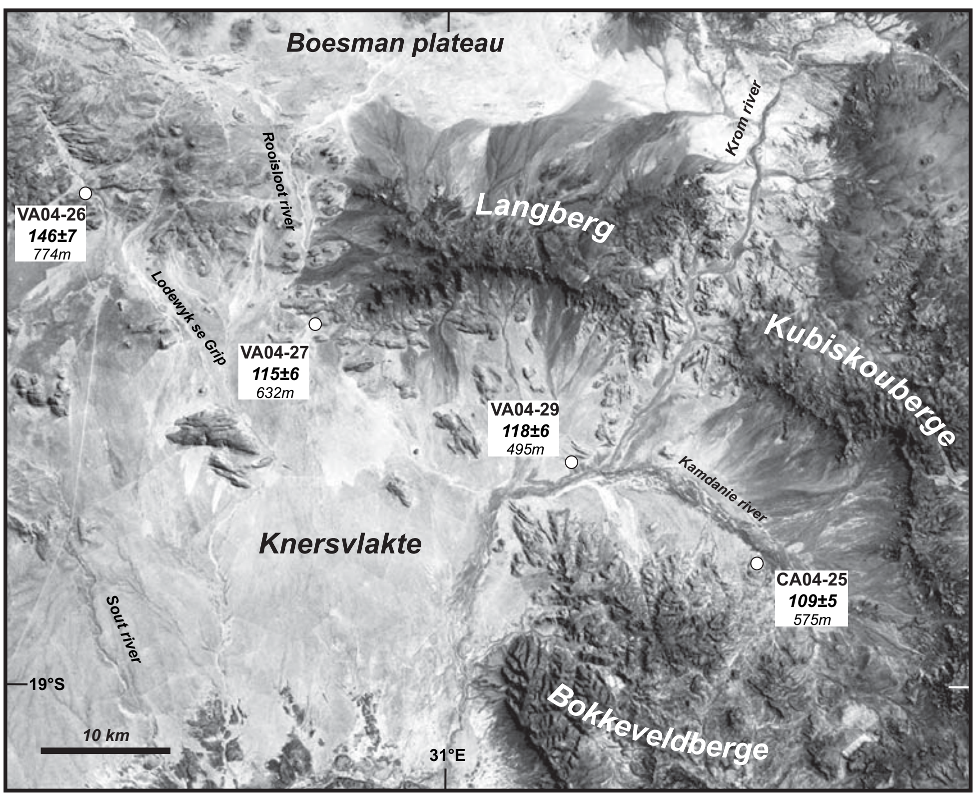

Figure 3. Landsat image of the study area with the location of the analysed samples, their elevation (in meters above sea level) and the obtained fission track ages.

Table 1. Apatite Fission Track results.

Sample number	Latitude (S)/ Longitude (E)	Alt. m	Lithology	Strat. division	Num. grains	ρd(Nd) (10^6 cm^{-2})	ρs(Ns) (10^6 cm^{-2})	ρi(Ni) (10^6 cm^{-2})	P(χ^2) (%)	U. conc. (ppm)	Central age ($\pm 1\sigma$)(Ma)	MTL($\pm 1\sigma$) (μm)	SD.(N) (μm)	Dpar (μm)
VA04/26	30.66929/18.7272	774	granitic gneiss	NMP	22	1.069(4292)	1.056(1335)	1.299(1642)	87	15	146.4 ± 7.2	13.78±0.16	1.63(106)	2.3
VA04/27	30.75859/18.89853	632	Bi gneiss	NMP	24	1.751(4687)	0.754(789)	1.187(1241)	99	13	115.3 ± 6.4	14.10±0.16	1.66(107)	2.03
VA04/29	30.85339/19.0971	495	gneiss	NMP	21	1.035(4146)	1.653(1988)	2.454(2951)	17	30	117.7 ± 5.5	14.28±0.13	1.34(112)	1.96
CA04/25	30.92178/19.23585	575	Bi gneiss	NMP	20	1.238(4292)	2.876(1757)	5.514(3369)	63	55	109.0 ± 4.8	13.59±0.14	1.53(125)	2.05

All ages are central ages (Galbraith, 1981). $\lambda D = 1.55125 \times 10^{-10}$. A geometry factor of 0.5 was used. Zeta = 341 ± 10 for CN5 glass. Irradiations were performed at the ANSTRO facility, Lucas Heights, Australia. P(χ^2) is the probability of obtaining χ^2 values for ν degrees of freedom where ν= number of crystals -1. ρd, ρs and ρi represent the standard, sample spontaneous and induced track densities respectively. MTL - mean track length. SD - standard deviation.

Dpar – mean track pit length. NMP - Namaqua Metamorphic Province.

temperature geochronology on the basement rocks across which this river is believed to have sculptured the paleolandscape.

Drainage system reconstructions for the Cenozoic are generally based on studies of contemporaneous sedimentary sequences as well as on the study of the geomorphology of the interfluves. For the Cretaceous, however, such an approach is difficult because there is limited direct geological evidence preserved. M.C.J. de Wit (1993) based his analyses on a detailed documentation of remnant Cretaceous paleoriver terrace deposits in existing *vleie* (wetlands) of the regions. Other reconstructions are based on offshore proxi-observations and analyses, such as sedimentation rates (Dingle and Hendey, 1984; Rust and Summerfield, 1990). Attempts at including paleotopography constraints in these models are even more challenging (*e.g.* de Wit, 1993).

Most of the thermochronological analytical tools currently used to test these issues provide relatively good estimates of cooling and denudation rates of rocks, but they do not provide information directly on the mechanisms of relief formation. However, low-temperature geochronological analysis (U-Th/He and apatite fission-track analysis) may be used with success to detect the presence and shape of the paleo-surfaces (*e.g.* paleo-topography; House *et al.,* 1998; 2001; Reiners *et al.,* 2003). This is because the cooling beneath ancient river valleys occur earlier than beneath intervening ridges and consequently the geometry of isotherms in the uppermost crust is sensitive to perturbations of the land surface (*e.g.* Stüwe *et al.*, 1994; Mancktelow and Grasemann, 1997; Braun, 2002). Thus the study of lateral age variations across areas of inferred drainage is a suitable approach to the reconstruction of the paleo-topography at the time (House *et al.,* 1998).

Most geomorphological studies agree that the present day Krom River valley is the likely location where the paleo-Karoo River also flowed towards the Atlantic Ocean (Figure 1). This can be best tested in the area known as the Knersvlakte, a large plain drained presently by the Krom River, where the Great Escarpment is poorly pronounced and is in places eroded by the Krom River and its tributaries (Figures 2 and 3). We applied apatite fission-track analysis (AFTA) to samples collected across the Krom River valley to test for the existence of a possible paleovalley linked genetically to a drainage network that existed at the time when the dated minerals cooled below their closure temperature. The Knersvlakte is an ideal testing ground because it is well established that data collected across landforms with wavelengths greater than 10 km can provide reliable information on the rate of relief evolution (*e.g.* Braun, 2002).

Field settings and sampling

The Knersvlakte is a hilly dry plain situated north of Vanrhynsdorp (Figures 2 and 3). Its altitude gradually rises from ~100 m in the southwest to 500 m in the

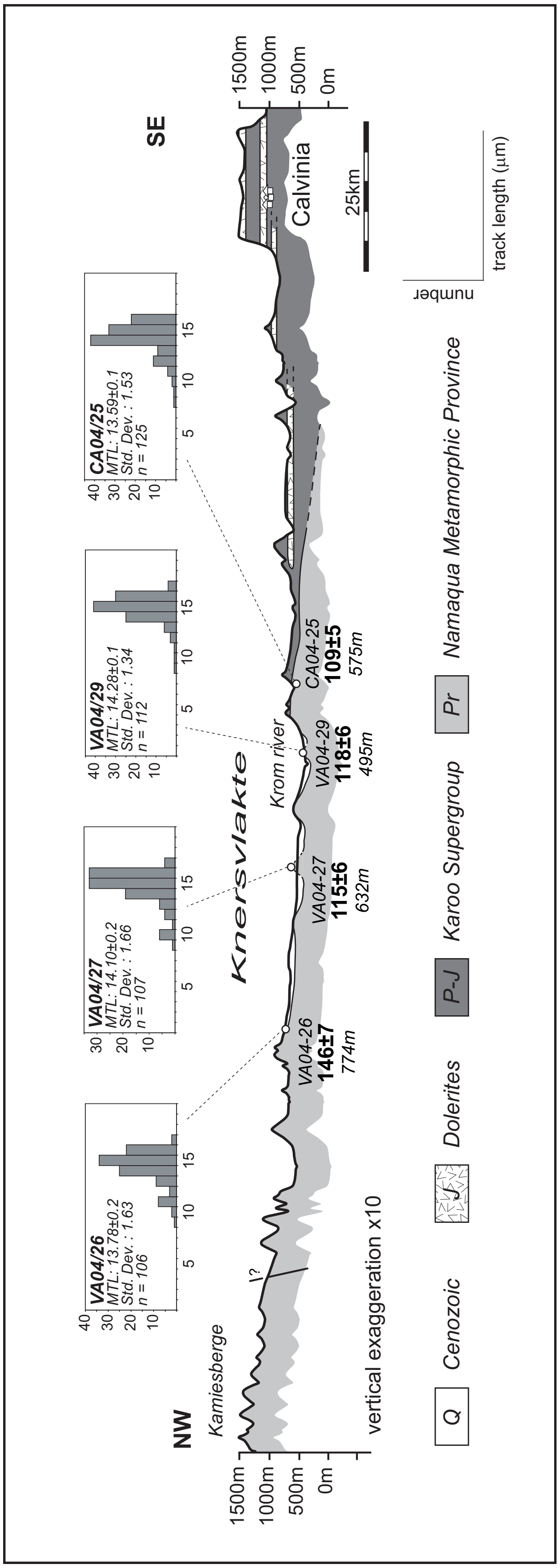

Figure 4. Profile AA' across the Knersvlakte area between Calvinia and the summits of the Kamiesberge with location of apatite fission track samples, relative ages and track length distribution histograms.

northeast. The plain is underlain by the high grade gneisses of the Mesoproterozoic Namaqualand Metamorphic Province (*e.g.* Joubert, 1971; Andreoli *et al.*, 2006) and the Neoproterozoic shales and siltstones of the Vanrhynsdorp Group (Johnson *et al.*, 2006). It is flanked to the west by the Hardeveld hills (up to 600 m high), underlain by Namaqua gneisses, and to the east by the Great Escarpment, and is drained by the Krom and Sout Rivers systems that originate on the high plateau to the east (Figures 2 and 3). Several flat-topped hills dissected by the Krom River and its tributaries represent remnants of the escarpment within the Knersvlakte plain (Figure 3). They are built of Karoo Supergroup siliciclastic sediments (Johnson *et al.*, 2006) and are intruded by subhorizontal Mid-Jurassic Karoo dolerite sills. To the northwest of Langberg (1032 m) the escarpment disappears and the Knersvlakte plain gradually merges with the approximately 1000 meters-high Boesman plateau (Figures 2 and 3).

Four samples of Namaqua granitic gneisses were collected for apatite fission-track analysis along a ~60 km long, northwest to southeast trending section through the northwestern edge of the Knersvlakte plain (Figure 2). The geographical location of the samples and the results are presented in Figures 3, 4 and Table 1.

Apatite fission-track analysis: methods and results

Whole rock samples were crushed and apatite grains were concentrated and recovered by conventional heavy liquid and magnetic methods. Apatite grains were mounted in epoxy resin, polished and etched with 7% HNO_3 at 21°C for 50 s. Irradiation was carried out at the ANSTO facility, Lucas Heights, Australia. Microscopic analysis was completed at the University of Cape Town using an optical microscope with a computer driven stage ("Autoscan" software from Autoscan Systems Pty. Ltd., Melbourne, Australia). All ages were determined using the ζ approach (Hurford and Green, 1983) with a ζ value of 341 ± 10 for CN5 standard (Table 1, analyst: A. Kounov). They are reported as central ages (Galbraith and Laslett, 1993) with a 1σ error (Table 1). The magnification used was x1250, at which horizontal confined track lengths and track etch pit diameters (Dpars) were also measured. Between 5 and 10 etch pits were measured per dated grain, depending on the quality and the density of the track pits on the grain surface. The Dpar values of the analysed samples vary between 2.0 and 2.3 µm with an average relative error of less than 5%.

The analysed samples yield AFT ages ranging between 146 and 109 Ma (Table 1). All samples pass the c^2 test and have mean track lengths between 13.59 and 14.28 µm with a standard deviation of 1.66 to 1.34 µm (Table 1). Track length histograms yield generally broad distributions (standard deviation 1.34 to 1.66 µm) with significant "tails" of short tracks (<~11µm; Figure 4). This implies partial shortening of old tracks, suggesting that these samples resided for a significant amount of time in the apatite partial annealing zone (APAZ) at

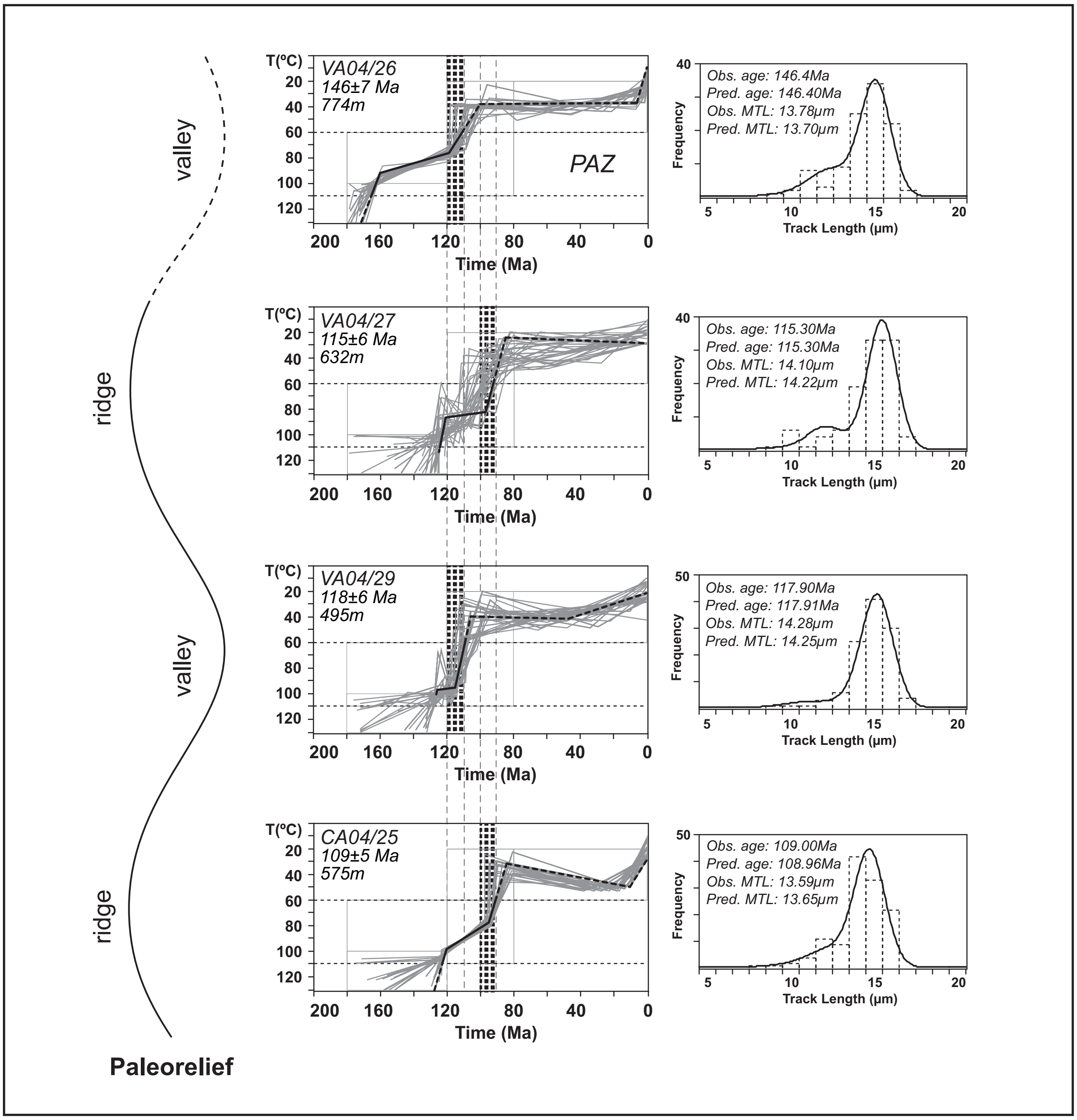

Figure 5. Modelled thermal histories for the analysed samples in relation to the inferred paleorelief (curve on the left hand side of the figure), and comparison between the predicted fission track parameters and the observed data. The shaded vertical bands represent episodes of cooling at 120 to 110 Ma and 100 to 90 Ma. The fine grey lines limit the user-defined time (t) -temperature (T) boxes. Horizontal dashed lines within individual models at 60 and 110°C bracket the partial annealing zone (PAZ) for apatite within the temperature limits assigned by Laslett *et al*. (1987). The thick black lines represent the best-fit paths and the grey lines the best 50 modelled paths. The dashed segments of the thermal histories at temperatures higher than 110°C and lower than 60°C indicate only a possible continuation of the reconstructed thermal history, because the annealing model cannot be used to predict thermal states out of the PAZ. MTL: mean track length.

temperatures between ~110° and 60°C before their final exhumation (*e.g.* Green and Duddy, 1989; Corrigan, 1993).

Thermal modelling

Fission tracks in apatites are formed continuously through time at an approximately uniform initial mean length of ~16.3 µm (Gleadow *et al.*, 1986). Upon heating, tracks gradually anneal and shorten to a length that is function of the time and maximum temperature to which the apatites were exposed. For example, tracks are completely annealed at a temperature of 110 to 120°C for a period of 10^5 to 10^6 years (Gleadow and Duddy, 1981). These annealing characteristics allow the generation of time-temperature paths by inverse modelling (*e.g.* Gallagher, 1995; Ketcham *et al.*, 2000).

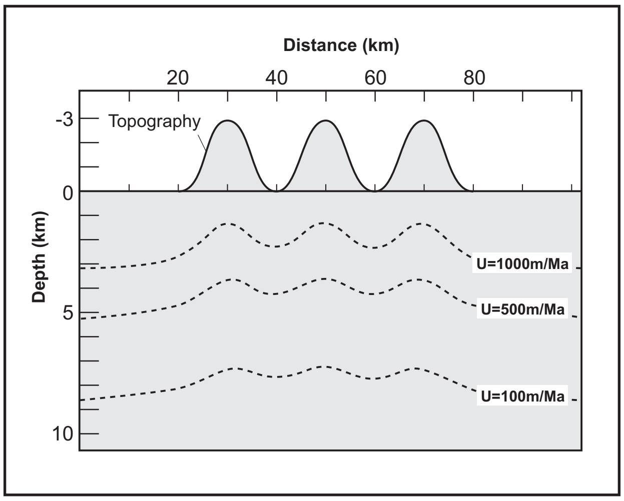

Figure 6. An example of the 100° C isotherm beneath a sine-shaped topography with amplitude H = 3 km and wavelength w = 20 km denuding at rates of U = 100, 500 and 1000 m/Ma (from Stüwe *et al.*, 1994).

The data were modelled to quantify site-specific time and amount of cooling along the traverse across the Krom River Valley. Modelling of the apatite age and track length distribution data was carried out with the program Monte Trax (Gallagher, 1995), using an initial track length of 16.3 µm. A Durango apatite composition was used with the Laslett algorithm in our models (Laslett *et al.,* 1987). Age and track-length distribution parameters, together with user-defined time (t) - temperature (T) boxes, were used as input data, allowing just one change of direction of the t-T path within each individual t-T box (Figure 5). In order to identify t-T points and thus define a cooling path, the program uses a genetic algorithm probabilistic approach (Gallagher and Sambridge, 1994) that optimizes the stochastic production of successive generations of thermal history models. The predicted fission-track parameters are then quantitatively compared to the observed (measured) values, and the level of consistency between the two sets is used to choose the thermal history that is most consistent with the observed data.

It has been shown that the annealing properties of apatites are controlled to a large extent by their compositional chlorine/fluorine ratio (*e.g.* Green *et al.,* 1986; Ketcham *et al.,* 1999; Barbarand *et al.,* 2003). Given that a positive correlation has been demonstrated between Cl weight % and apatite Dpar (Donelick, 1993), we measured systematically Dpar in the dated samples (Table 1). Three of the modelled samples have Dpar values between 1.96 and 2.05 µm (Table 1). This is lower than the value we obtained for the Durango apatite standard (2.36 ± 0.02 µm; n = 100) etched under the same conditions used for all our samples. Therefore our dated apatites are probably more F -rich than the Durango standard and consequently may have been annealed at temperatures slightly lower than those indicated by the models. The estimated magnitude of the relative annealing temperature variations due to compositional difference is about ± 20 °C (Burtner *et al.,* 1994). Therefore the net amount of denudation in our case would be slightly overestimated by modelling, but the timing of the cooling events would remain unaffected.

Information on the older thermal history of the samples is also an important input to the models. The last significant thermal event that affected the Namaqualand metamorphic province was the late Precambrian Pan-African orogeny, which in this region peaked around 550 Ma (*e.g.* Frimmel and Frank, 1998; Frimmel, 2000). The time of post orogenic cooling is not known. Most probably the study area was entirely covered by the Permo – Triassic Karoo deposits, including Karoo doleritic sills that commonly cap the surrounding hills. Duane and Brown (1991) suggested maximum paleotemperatures of 200 ± 25 °C at ~190 Ma for the Karoo sediments based on fission-track data from detrital zircons. AFT ages can therefore be interpreted as fully reset during the Karoo igneous event (~183 Ma; Duncan *et al.,* 1997).

Time-temperature boxes in our models were defined for three main time intervals: 180 to 120 Ma, 120 to 80 Ma and 80 to 0 Ma (Figure 5). These periods correspond to the three distinct phases of accelerated cooling in southern Africa reported in previous studies (Brown, 1992; Brown *et al.,* 2002; Raab *et al.,* 2002; Tinker, 2005; Tinker *et al.,* 2008a, b; Kounov *et al.,* in press).

Thermal models from our study reveal a distinct phase of relatively fast cooling to temperatures below 60°C between 120 and 90 Ma, (Figure 5). In detail, the four modelled samples can be separated into two groups. Samples VA04/26 and VA04/29 show relative fast cooling between 120 and 110 Ma whereas samples VA04/27 and CA04/25 show a similar fast cooling only at a later stage, between 100 and 90 Ma (Figure 5).

Although there is a hint of possible rapid cooling events at 180 to 170 Ma (VA04/26) and 130 to 120 Ma (VA04/27, 29 and CA04/25) the best fit curves predict rather slow cooling from 160 Ma until 120 to 100 Ma (Figure 5).

Discussion

AFT low-temperature thermochronology provides information about the rate at which rocks cool as they are exhumed within the uppermost crust (~2 to 6 km). Because the temperature structure of the uppermost crust, to which this method is most sensitive, is perturbed by the surface topography (Stüwe *et al.,* 1994; Mancktelow and Grasemann, 1997; Braun, 2002), fission-track analysis can be used to indirectly provide information on the shape of the paleo topography and the rates at which this evolves when the rocks cool through the system closure temperatures (*e.g.* Braun, 2002, 2005). Topography perturbs local geotherms to a depth that depends on the vertical and horizontal scale of the surface relief as well as on the exhumation rate.

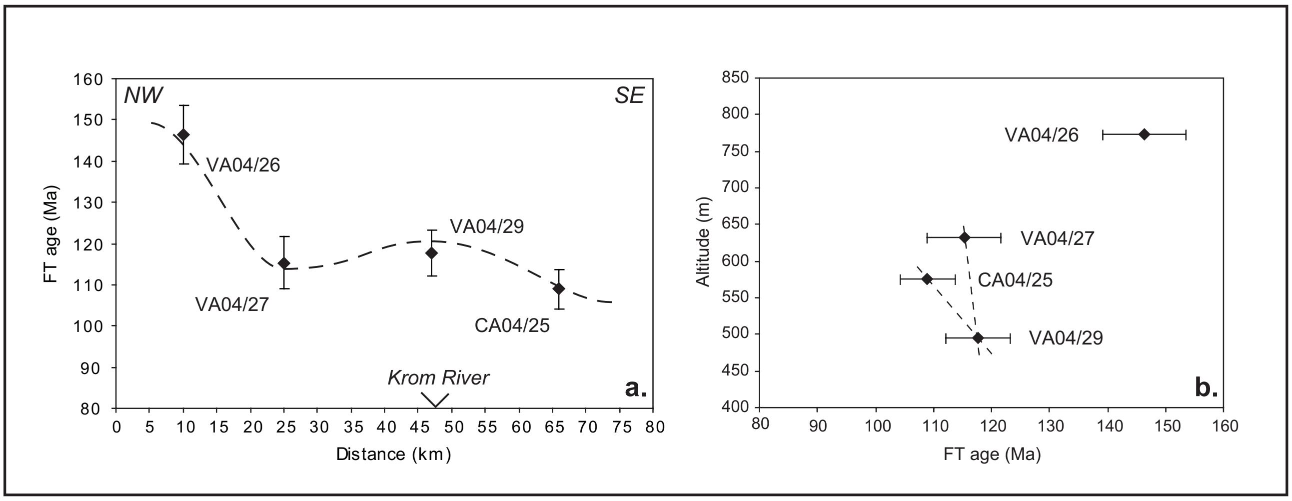

Figure 7. Apatite fission track ages vs. distance along the profile A A' (Figure 2) (**a**) and elevation (**b**).

Numerical models show that even at low exhumation rates (less than 0.5 mm/a) the 100°C isotherm will be affected by a sine-shaped topography with an average wavelength of 20 km (Figure 6; Stüwe *et al.,* 1994; Mancktelow and Grasemann, 1997; Braun, 2002). With this in mind, the existence of a paleorelief can be estimated even if the area underwent a significant decrease in surface relief after the time when the rocks cooled through the closure temperature.

The apatite ages plotted along section A–A' (Figure 2) reveal a sinusoidal age profile (Figure 7a) suggesting that different sites experienced different amounts of denudation. In addition, the lack of positive correlation between the altitude and the age of the analysed samples (Figure 7b) shows that their age difference is not related to the uniform denudation of the whole area between 160 and 100 Ma, a situation where samples that are situated higher in the rock column cooled through the closure temperature before those deeper down and therefore have older ages (*e.g.* Viola *et al.,* 2003). The relatively older age of the highest sample VA04/26 could partially reflect the fact that it also has a higher Dpar value. Sample VA04/29, which was collected from the lowest altitude (495 m) at the bottom of the valley, yielded an AFT age of 118 ± 6 Ma, slightly older than sample VA04/27 (632 m) age 115 ± 6 Ma, collected from the topographically higher interfluve between the rivers Krom and Rooisloot, and than sample CA04/25 (575 m) age 109 ± 5 Ma, collected from the gentle slope of Kamdanie river valley (Figures 3 and 4).

We suggest that the FT age distribution of the samples collected across the Krom River Valley is the direct consequence of the paleotopography developed during their cooling through the apatite PAZ. Based on these results we conclude that, during cooling through the APAZ, VA04/29 was located beneath a paleo-valley (*i.e.* a topographic low with significantly less overburden), whilst the two other younger samples (VA04/27 and CA04/25) resided below high topographic ridges. In this interpretation, relief must have been significant at that time, with deeply incised valleys and high average topography to produce such a distinct disturbance in the thermal isochrons (Figure 8a). We suggest that sample VA04/26 was located in a position corresponding to the incision of a paleovalley similar to sample VA04/29 because it yielded an age older than VA04/27, situated in the present day interfluve (Figure 8a).

Clearly, the main problem of this model is the paucity of data points and the fact that some of the ages overlap within the error limit. This can, however, be partially overcome by the comparative analysis of the thermal modelling of the analysed samples and by integrating these results with other AFT ages from the literature.

Our AFT models are consistent with the presented model. Samples VA04/26 and VA04/29, interpreted to have been located below the river valley at the time of cooling, experienced relatively fast cooling between 120 and 110 Ma, that is about 10 Ma before the other two samples (VA04/27, CA04/25) interpreted to have been located deep beneath the shoulders of the valley. We interpret this differential cooling to be related to intense channel erosion triggered by uplift of the catchment area (Figure 8a). Such a period of tectonically-induced uplift during the Mid Cretaceous along the western coast of South Africa has already been suggested by previous studies (Brown *et al.,* 1990; Brown, 1992; Kounov *et al.*, in press).

Samples from the interfluves instead underwent very slow cooling in the same time interval (Figure 5 and 8). This can be explained by the fact that the interfluves reacted to these changes more slowly than the actively eroding channels (Burbank and Anderson, 2001). Only once channel incision increased the hillslope gradient, did hillslope erosion and eventually interfluve degradation (Figure 8b) become more effective. We tentatively suggest this to be the process responsible for the later increased cooling phase detected between 100 and 90 Ma for samples VA04/27, CA04/25 (Figures 5 and 8b). Since 90 Ma, all analysed samples were

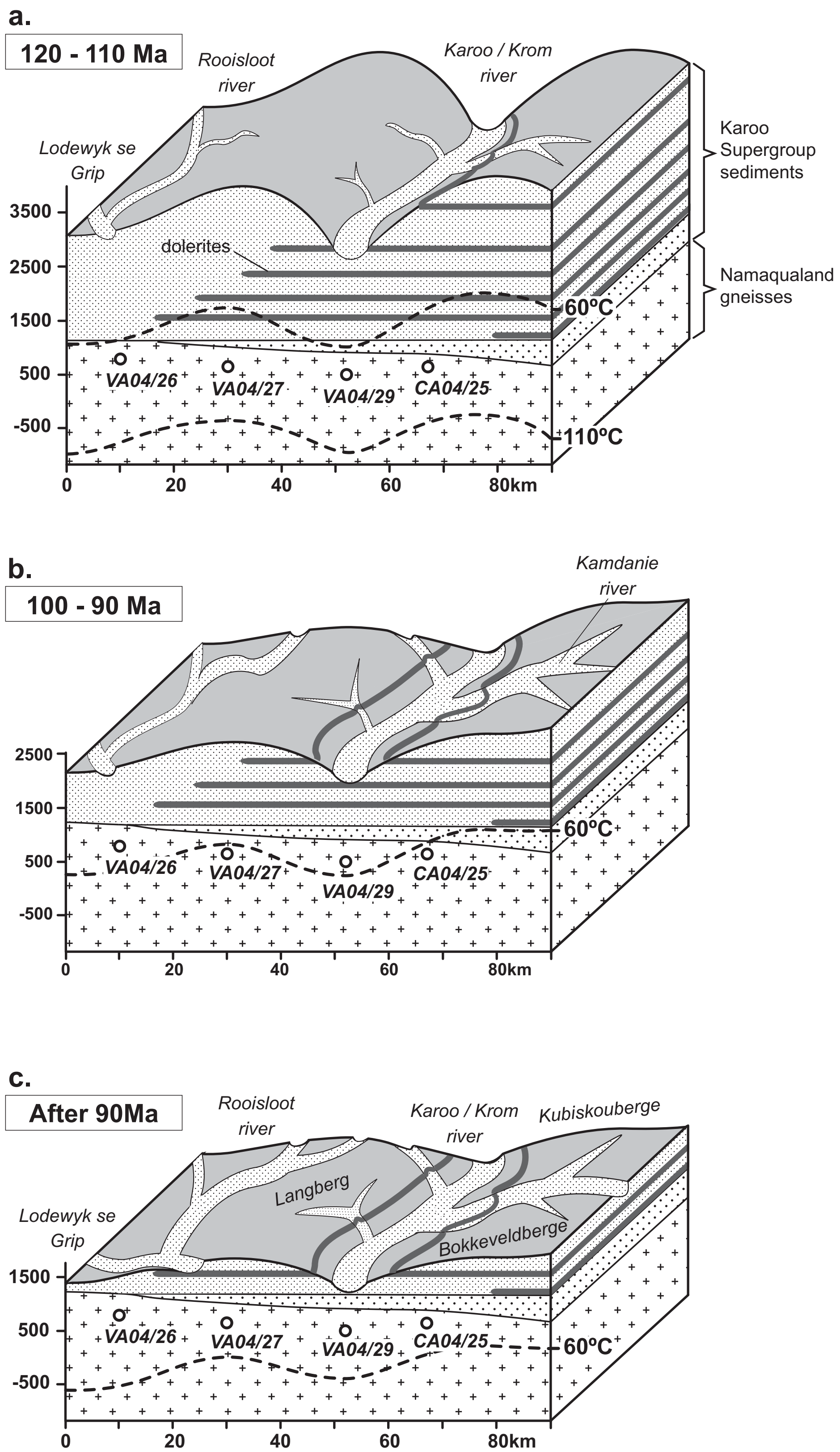

Figure 8. Block diagram illustrating the denudation evolution of the study area from 120 to after 90 Ma. Dashed lines represent 60 and 110°C isotherms at depth calculated for a geothermal gradient of 30°C/km.

exhumed to depths corresponding to temperatures below 60°C (~2 to 3 km), beyond the resolution of the AFT method (Figure 8c). Subsequent erosion created the present relief and caused the present day negative slope of the age-altitude plot (Figure 7b; Braun, 2002).

This scenario is further supported by AFT results reported by Kounov *et al.* (in press) from the coastal plain south of the study area (Figure 2). Three samples collected in the vicinity of Vanrhynsdorp (Figure 2) show similar age patterns to those presented in this study. Sample CA04/06, collected from the lowest altitude (35 m), along the Olifants river valley, yielded an older AFT age (98 ± 7 Ma) than samples CA04/10 (86 ± 5 Ma, 102 m) and CA04/11 (95 ± 6 Ma, 259 m), collected from the topographically higher slope of Krom/Olifants river valley (Figures 1 and 2). Although in absolute terms the FT ages of the samples from the Vanrhynsdorp area are slightly younger than those presented here (Figure 1), the modelling of samples CA04/10 and CA04/11 (Kounov *et al.,* in press) reveals a significantly similar thermal evolution, with a fast cooling episode at about 100 to 90 Ma. The data suggest that active valley incision was not only taking place in the escarpment area but also in the present day coastal plain.

The presence of deeply incised (>1000 m) canyons in the Mid Cretaceous suggests indirectly the existence of a major river system in the study area at that time. This supports paleogeographic reconstructions having the paleo-Karoo River (that drained most of the South African continental interior during the Cretaceous) flowing through the Knersvalkte before it reached the Atlantic Ocean. Since the end of the Cretaceous, active erosion, probably in the absence of significant uplift (*e.g.* Tinker *et al.*, 2008 a; b; Kounov *et al.*, in press), modified the topography of the area and left behind only minor remnants of the previously existing mountain chain, such as the Langberg and Kubisouberge hills, rising only at about 500 m above the present valley bottom (Figure 3).

Conclusions

Apatite fission-track analysis on samples from across the Knersvlakte plain in the coastal area of western South Africa reveals the existence in the Mid Cretaceous of a well developed paleo-relief, characterised by a sharp topography. This paleo-relief consisted of a deeply incised valley flanked by elevated ridges. This valley coincides spatially with the present course of the Krom River through the Great Escarpment. We suggest that the Karoo River and its tributaries most likely caused this relief, providing a major outlet to the Atlantic Ocean for its inland drainage system. Since the end of the Cretaceous the continuing erosion modified the local topography creating the present day low relief of the area.

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Editorial handling: L. D Ashwal