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The Central Zone of the Damara Orogen, Namibia, as a deep metamorphic core complex

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Mapping of dome structures in the Central Zone of the Damara Orogen, Namibia, has shown that there is a profound ductile shear zone, named the Khan River Detachment, separating the ~2 to ~1 Ga granitic basement gneiss domes from the ~550 Ma metamorphosed Damaran sedimentary cover. Kinematic indicators show that the hanging wall of the detachment has moved towards the SW and is extensional. Different levels of the Damaran stratigraphy have been brought down into tectonic contact with the basement. There is no repetition by thrusting. The domes are thought to be the result of combined crustal NW-SE compression and SW-NE extension when the cover became detached from the basement and escaped and flowed towards the SW following collision of the Kalahari and Congo Cratons. The apparent coincidence of 1) a regionally extensive detachment zone that can be extrapolated from dome to dome for over 9000 km^2; 2) consistent kinematic indicators for SW directed extensional detachment of the Damaran cover from its basement; and 3) syn-detachment granite magmatism: suggests that the geology can be explained by a deeper mid-crustal version of the North American metamorphic core complex model.

Introduction

The purpose of this paper is to examine the relationship between the dome structures (e.g. Smith, 1965) and the newly described (Oliver, 1993; Oliver, 1995) basement-cover detachment structures from the Central Zone of the Damaran orogenic belt of Namibia and to see if they can be explained by the metamorphic core complex model (Crittenden *et al.*, 1980).

The Damaran orogenic belt of central Namibia can be divided into three main tectonostratigraphic zones: 1) a Central Zone of high-temperature low-pressure metamorphosed sediments with inliers of basement gneiss domes and abundant granite plutons; 2) a Northern Zone of N thrusted low-grade metamorphic rift volcanics and sediments with intrusive granites; and 3) a Southern Zone consisting of a SE thrusted low-temperature, high-pressure metamorphosed accretionary prism sequence (Miller, 1983). The Northern Zone structures generally trend ENE-WSW but near the coast they swing NW into the Kaoko Belt. Inland the Southern Zone has the same ENE-WSW structural trend but at the coast it swings SW out to sea. The inset to Fig. 1 illustrates the distribution of these zones.

The stratigraphy of the Damaran sequence is well known in the area shown in Fig. 2. Etusis Formation metaquartzite, arkose and conglomerates are considered either to be in unconformable contact (Smith, 1965) or in tectonic contact (Oliver, 1993 and 1995) with basement gniesses and meta-granite. In this area the basement granite gneisses have been SHRIMP zircon dated at 1038 ± 58 Ma by Kröner *et al.* (1991). The Rössing Formation of pelitic biotite schists, metaquartzites, and minor marbles succeeds the Etusis Formation and is itself succeeded by the Khan Formation of metagreywacke greenshists. Next there is a sequence of mixtite/glaciomarine metasediments of the Chuos Formation. The Karibib Formation of massive dolomitic marbles follows next with the pelitic Kuiseb Formation of biotite schists lying at the top.

Smith (1965) suggested a polyphase deformation history for the area. His scheme has a first fold phase of upright D_1 anticlines and synclines originally oriented SE-NW. A second fold phase, oriented NNE-SSW, then refolded the first folds to produce an interference pattern of open domes and sharp keels generally oriented NE-SW. A set of upright very open N-S-trending third folds then interfered with these previous folds to produce the present day outcrop pattern. Reports of thrusting summarised in Miller (1983) have not been confirmed in this work.

Dome Structures

Dome structures in the Central Zone of the Damara Orogen are easily recognised using ground mapping and Landsat remote sensing techniques. Marbles make particularly good marker horizons. The mapping of Smith (1965), Jacob *et al.* (1983) and Kröner (1984) shows that the domes tend to be elongated in the NE-SW direction with dimensions varying from 10 x 20 km to 10 x 40 km (see Fig. 1). The domes are often asymmetric with the NE-facing sides dipping moderately to the NE whilst the SW facing sides are either steeply dipping to the SW, vertical or overturned so that they also dip moderately or steeply to the NE. NW and SE flanks of domes are usually moderately to steeply dipping. Fig. 2 illustrates various examples. This morphology is similar to that described elsewhere for gneiss domes in high-grade terrains of Zambia (Stillman & de Swardt, 1965), Zimbabwe (Talbot, 1973), New England (Talbot, 1977), and New Zealand (Gibson *et al.*,1988; Oliver, 1991). Domes in the Central Zone are characterised by the occurrence of cores of granitic augen gneiss known locally as the Abbabis Gneiss, which Smith (1965) and Miller (1983) refer to as basement.

Several hypotheses have been proposed to explain dome structures: (1) interference of regional-scale folds

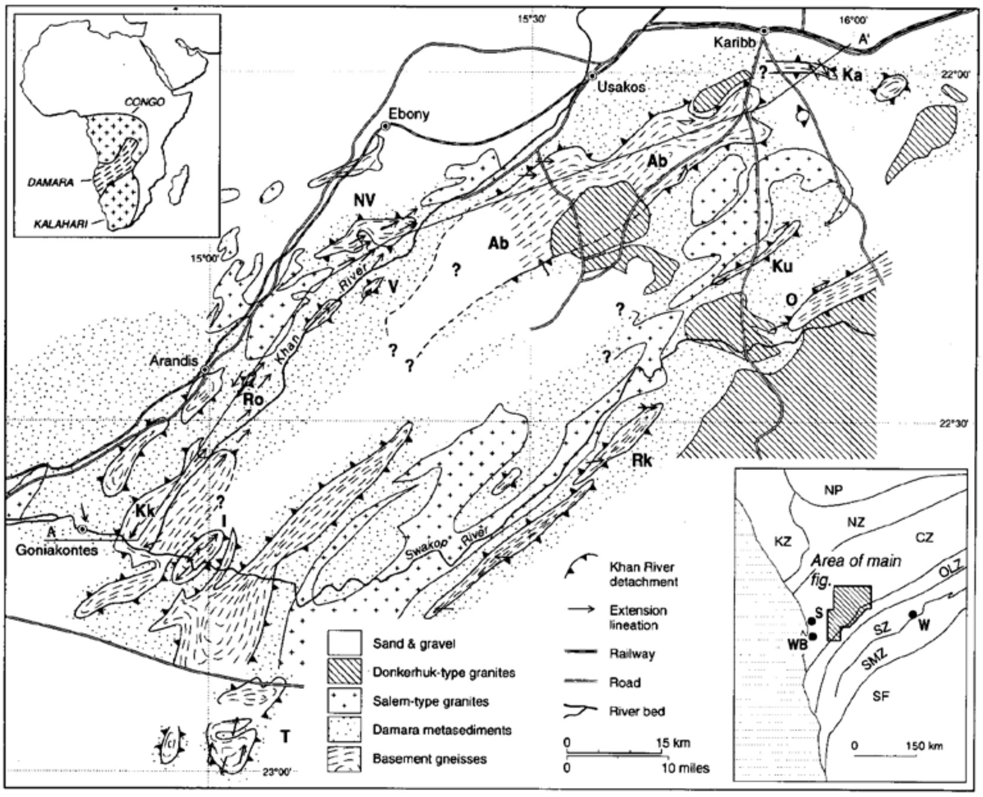

Figure 1: Lower inset shows location map for the Central Zone of the Damara Orogen. Upper inset shows location of the Damara Orogenic Belt in southern Africa. Main map shows the basement domes mentioned in the text (modified from Smith, 1965; Miller and Hoffmann, 1981). Abbreviations: NP = Northern Platform (Congo Craton), KZ = Kaoko Zone, SMZ = Southern Margin Zone, SF = Southern Foreland and Platform (Kalahari Craton), S = Swakopmund, WB = Walvis Bay, CZ = Central Zone, NZ = Northern Zone, OLZ = Okahandja Lineament Zone, SZ = Southern Zone. The Khan River Detachment is taken to be the bottom of the Damara sequence as shown on Smith's (1965) map. Ab = Abbabis Dome; I = Ida Dome; Ka = Karibib Dome; Kh = Khan Dome; Ku = Kuduberg Dome; NV = Namibfontein-Verenoeg Domes; O = Otjimbingwe Dome; Rk = Rooikuiseb Dome; Ro = Rössing Dome (and mine); T = Tumas Dome; V = Valencia Dome. Cross sections of several domes are shown on Fig. 2. Cross section AA' given on Fig. 6. Each extension lineation symbol represents the average of many readings. The author has spent 10 weeks in the area, mapping the basement-cover detachment on Landsat and 1:50 000 topography maps and at critical locations on each dome at a scale of 1:5 000 using compass and pacing.

(E.g., Smith 1965: Barnes & Downing 1979); (2) buoyant rise of diapirs of granitic basement into the meta-sedimentary cover (Ramberg, 1972; Eskola, 1949); (3) ballooning of basement-derived granites intruding anticlinal structures of a meta-sedimentary cover (Kröner, 1984); (4) sheath folding within shear zones (Coward, 1980); (5) doming over metamorphic core complexes (Crittenden *et al.*; 1980: Lister & Davif 1989). Oliver (in press) suggests a sixth method based on the analyses of Smith (1977, 1979) and Ramsay (1967) whereby domes form as a combination of constructional shortening and Ramsay class 3 folds in which all the horizontal directions are contractional. In this way domes can form during one phase of sinistral transpressional collision between the Congo and Kalahari cratons (Oliver, 1995). This hypothesis does not require interfering folds or diapirism or magmatic ballooning. It is supported by the apparent lack of re-folded folds seen in the field at outcrop scale.

The Khan River Detachment.

Mapping by Oliver (in press) of the dome structures in the lower Khan River has shown that there is a profound ductile shear zone, which he named the Khan River Detachment, separating the 1038 ± 58 Ma granitic basement gneiss from the 571 ± 64 Ma metamorphosed Damaran sedimentary cover (SHRIMP zircon age dates quoted from Kröner *et al.*,1991). The contact between basement and cover has been investigated in 12 different domes: the features of each contact is summarised in Table 1. In every case there is field evidence for a tectonic break between cover and its basement. Furthermore, for over 9000 km of the study area, the same Damaran cover sequence is seen in tectonic contact with basement. It seems probable that this contact can be correlated on a regional scale as the same detachment. The Otjimbingwe Dome (see Fig. 1) is cored by a alkaline syenite complex which, considering its tectonised fabrics, is an early tectonic intrusion. The SW

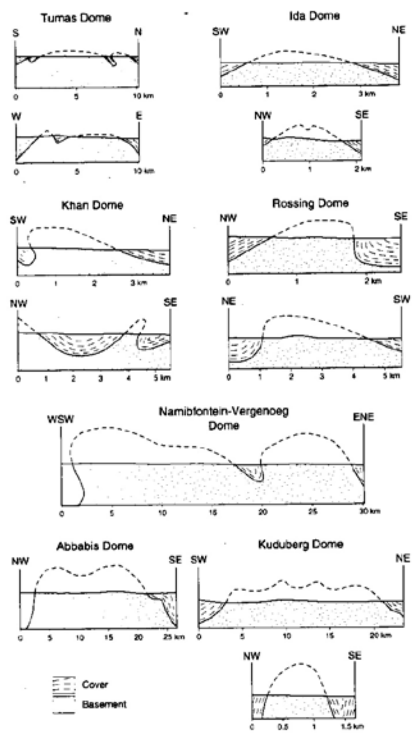

Figure 2: Cross-sections of basement domes shown on Fig. 1. Tumas Dome section from Jacob *et al.* (1983); Namibfontein-Vergenoeg section from Kröner (1984); other sections drawn from Smith (1965) and from the author's field mapping.

termination of the intrusion appears to be surrounded by Etusis metaquartzites. This dome is therefore different from the others in that it is not cored by the 1-2 Ga basement, however, like the others it shows an impressive detachment shear zone at the base of the Damaran sequence (see Table 1).

Various kinematic indicators have been mapped: e.g. asymmetric strain shadows around rotated phenocrysts in basement metamorphosed granites, around porphyroblasts in metasediments of the cover, and around strained pebbles in the cover (Berthe *et al.*, 1979; Cobbold & Gapais, 1987; Hooper & Hatcher, 1988); sense of shear in higher strain shear bands as seen by the deflection of foliation (Simpson & Schmid, 1983; Simpson & Depaor, 1993), sense of vergence shown in fold profiles, imbrication of broken and displaced porphyroclasts (Simpson & Schmid, 1983), and CIS fabrics (Berthe *et al.*, 1979). Table 1 summarises this information: in nearly every case it can be shown that the hanging wall of the detachment has moved towards the W or SW. One exception is the Karibib Dome where it appears that the hanging wall has moved towards the SE. An other exception is on the SE side of the Abbabis Dome where a post -detachment shear zone has tectonised the contact such that the hanging wall has moved up to the NNW. Nowhere in this portion of the Central Zone has any repetition of Damaran stratigraphy been mapped and this is taken to indicate that thrust tectonics did not operate. This being the case then the detachment, by elimination, ought to be extensional. This has been confirmed in the Khan and Ida Domes where the geometry of deflected foliation in higher strain shear zones within the detachment shows extension (see Fig. 7 in Oliver, 1995).

Pebble dimensions have been measured in the detachment shear zone for several domes. When plotted on Flinn (1958) diagrams the majority fall in the constructional *L*-tectonite field (see Fig. 3). Aspect ratios of <10:1:1 are not uncommon and are elongated NE-SW along the length of the orogen, parallel to the axes of periclinal synclinoria in the Damaran cover and parallel to the long axes of the more open elongate dome structures in the basement gneisses (see Fig. 1). It is notable that *L-S* tectonised basement gneisses have flattened rod shaped quartz-feldspar aggregates with aspect ratios of ~10:2:1, also oriented NE-SW; *L* tectonites have similar elongate mineral aggregates but with aspect ratios of ~10:1:1. These values for the detachment zone tectonites from the basement cannot be used for precise strain measurements but they indicate that the deformation process occurred in the constructional domain. *L-S* tectonites can be recognised for a maximum of 2 km above and below the Khan River Detachment.

Fig. 4 a-d presents cartoons to illustrate the concept

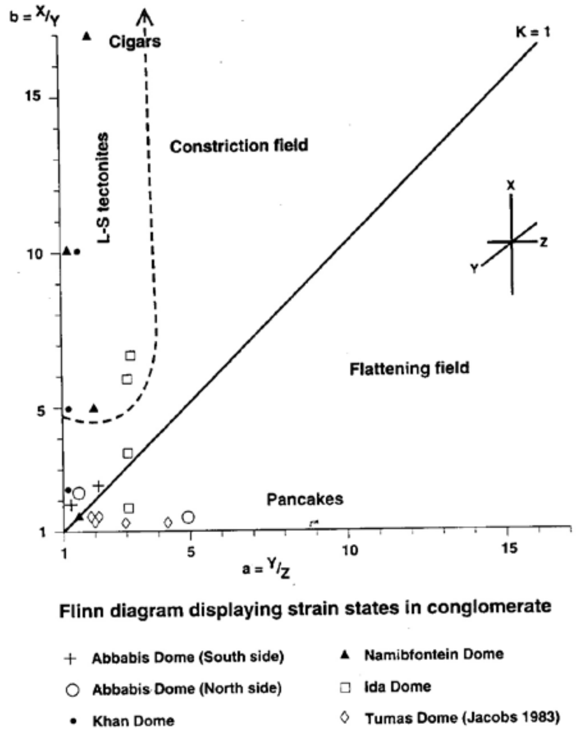

Figure 3: Flinn (1958) diagram of pebble dimensions from conglomerates in the Etusis Formation, deformed in the shear zone of the Khan River Detachment. Dashed line is the area in which basement rodded L-S tectonites fall : quartz-feldspar aggregates are cigar shaped and have X/Y ratios >5 and commonly 15.

of dome and detachment formation in a constructional domain of the middle crust of the Damara Orogen: Fig. 4a shows effect of layer parallel shortening on materials with different viscosity ($\mu_1<\mu_{2D}$) undergoing pure shear, (after Smith, 1979). Note that the competent layer (i.e. the basement μ_2) has flowed into broad anticlines whilst the incompetent layer (i.e. the cover μ_1) has flowed into tighter synclinal mullions. Fig. 4b shows the effect of shortening in two directions (i.e. constriction and thickening) to produce doming when the principle ductile strains became constructional, i.e. $1\lambda_1>\lambda_2$ (see Ramsay, 1967, Fig. 3.54, field 3). Without the recognition of the doming effects of constriction, the doming might be interpreted as the effect of two fold phases. Gosh and Ramberg (1963) derived almost identical doming in *one phase* constructional buckling experiments on builders putty. Significantly different results were obtained en-when putty was first layer parallel shortened in one direction and *later* shortened at right angles to the first direction.

Fig. 4c shows that the effect of extension parallel to the orogenic trend is to extend and elongate the domes producing extension lineations parallel to the long axes of the domes. At this stage the stretching lineation would be generated in a field of pure shear. Fig. 4d shows the effect of plastic failure during simple shear along the cover-basement contact to produce a mid-crustal detachment after the crust has thickened (as in 4b), failed, flowed and escaped (as in 4c). The dome shaped detachment surface (a ductile shear zone) has been dragged out into km-scale sheath folds. In this way the fold profiles illustrated in Fig. 2 may have been produced. The domes are thought to be the result of combined crustal NW-SE compression and SW-NE extension when the Kalahari and Congo cratons collided, the orogen collapsed and the cover escaped and flowed towards the SW (Oliver in press). This is similar to that which has been proposed for the extrusion of the E Himalaya after India had indented Asia (Tapponnier *et al.*, 1982). Fig. 4 c and d are in a possible time sequence.

The domes are massively invaded by granite, some of which cut the detachment. Table 1 lists the kinds of granite found in the vicinity of the detachment in the various domes. The most common granite type is a non-foliated pegmatitic alkali leucogranite (locally known as alaskite) which intrudes as sheets which tend to (but not always) follow the stratigraphy around dome structures as sills and dykes. In places these sheeted complexes

	Lithologies at contract Basement	Cover	Intrusion at contact	Tectonite Fabrics	Hangingwall movement direction	Evidence for movement	Thickness of detachment shear zone
Tuma Dome	mylonnitised granitic augen gneiss	mylonitised meta-conglomerate[1]	leucogranite	L+LS tectonites	to the SSW	folds, pebble+augen strain shadows,	200m
Ida Dome augen gneiss	mylonnitised granitic conglomerate[2]	mylonitised meta-granite	leucogranite	L+LS tectonites	to the SW	augen strain shadows	50m
Khan Dome	mylonnitised granitic augen gneiss	mylonitised meta-quartzite granite	grey granite	L+LS tectonites	to the SW	folds,augen strain shadows high strain zones	max 2km min 50m
Rossing Dome	mylonitised metaquarttzite	mylonitised metaquarttzite	pegmatitic granite	LS tectonites	to the SW	high strain zones	200m
Valencia Dome	mylonitised granitic augen gneiss	marbles	grey granite	LS tectonites	to the SW	augen strain shadows	200m
Namibfontein-vergenoeg Dome	mylonitised granitic augen gneiss	mylonitised metaquarttzite	pegmatitic granite	L+LS tectonites	to the SW	augen strain shadows	500m
Abbabis Dome -NW side	mylonitised granitic augen gneiss	mylonitised metaquarttzite	pegmatitic granite	L+LS tectonites	to the W	augen strain shadows	+300m
Abbabis Dome -NE side	mylonitised granitic augen gneiss	mylonitised meta-conglomerate[3]	pegmatitic granite	L+LS tectonites	to the W and SW	augen strain shadows pebble strain shadows	+500m
Abbabis Dome -SE side	mylonitised amphibolite, mylonitised granitic augen gneiss	mylonitised meta-conglomerate[4]	nil	L+LS tectonites	to the NNW	C/S fabric in post-detacment shear zone	+500m
Karibib Dome	mylonitsed diorite augen gneiss	mylonitised marbles	nil	LS tectonites	to the SSE	augen strain shadows	+500m
Kuduberg dome	mylonitised granitic augen gneiss	mylonitised metaquartzite	nil	L+LS tectonites	to the SW	augen strain shadows imbricated porphyroclasts	50m
Otjimbingwe Syenite	mylonitised synenitic augen gneiss	mylonitised mica schist	diorite	L+LS tectonites	to the SW	augen strain shadows imbricated porphyroclasts	300m
Rooikuiseb Dome -NE end	mylonitised granitic augen gneiss	mylonitised metaquartzite	grey granite	LS tectonites	to the W	augen strain shadows,fold vergence,high strain zones	100m
Rooikuiseb	mylonitised granitic augen gneiss	mylonitised metaquartzite	grey granite	LS tectonite	to the WSW	augen strain shadows	100m

Notes: 1) pebbles of quartz, metaquartzite, gneiss, granite; 2) pebbles of quartz, metaquartzite; 3) pebbles of quartz, metaquartzite, mafic biotite schist; 4) pebbles of quartz, metaquartzite, amphibolite.

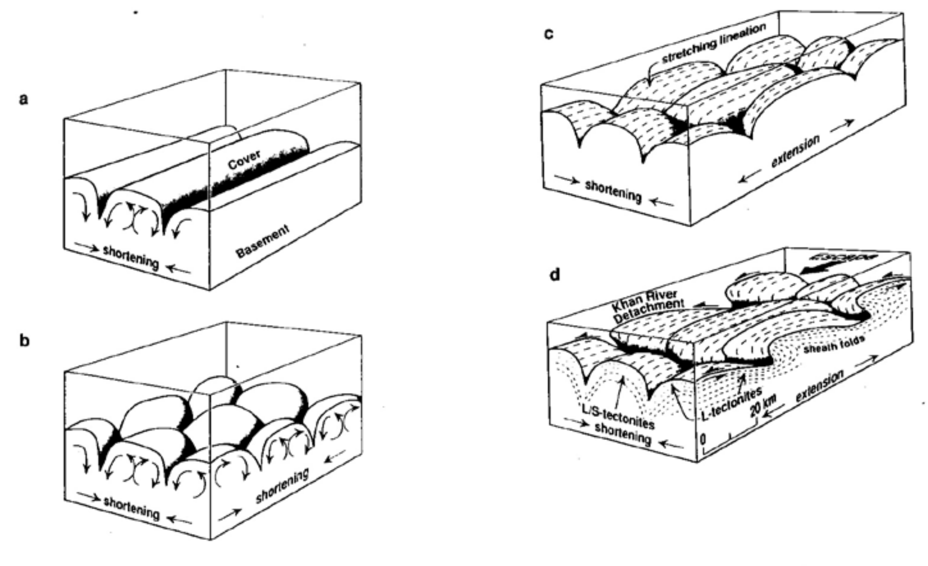

Figure 4: Cartoons to illustrate the concept of dome and detachment formation in the middle crust of the Damara Orogen: a) effect of layer parallel shortening on materials with different viscosity ($\mu_1 > \mu_2$) undergoing pure shear, (after Smith, 1979). Note that the competent layer (i.e. the basement μ_2) has flowed into broad anticlines whilst the incompetent layer (i.e. the cover μ_1) has flowed into tighter synclinal mullions; b) effect of shortening in two directions (i.e. constriction and thickening) to produce doming: this might be interpreted as the effect of two fold phases; c) effect of extension parallel to the orogenic trend is to extend and elongate the domes producing extension lineations parallel to the long axes of the domes; d) effect of plastic failure along the cover-basement contact to produce a mid-crustal detachment after the crust has thickened (as in b), failed, flowed and escaped (as in c). The dome shaped detachment surface (a ductile shear zone) is dragged out into sheath folds. Modified from Oliver (1995).

'Table 2. Summary of 'reliable' age dates from Central Namibia.

Rock-type, mineral locality.	Method	Age Ma	Event	Reference
Schist, biotite; Khan-Swakop R	K/Ar	429±17	Biotite Cooling(300°C)	Clifford 1967
Shists, biotite, Khan-Swakop R	Rb-Sr	448-465±5	Biotite Cooling(350°C)	Hawkesworth et al. 1983
Diorite, hornblende; Otjozondjou.	$^{40}Ar/^{39}Ar$	478±4	Hornblende cooling(550°C)	ditto
Donkerhuk granite, Otjimbingwe	U-Pb	505±4	Intrusion, late tectonic	Kukla et al. 1991
Alaskite,zircon, uranitite,monazite Goniakontes	U-Pb	508±2	intrusion, post-tectonic doming	Briqueu et al. 1980
Khan Fm, monazite Goniakontes	U-Pb	510±3	Syn-metamorphic growth	ditto
Salem granite zircon; Goas	U-Pb	512±40	Syn-metamorphic granite intrusion	Allsopp et al. 1983
Okongava diiorite,zircon	U-Pb evaporation	516±6.3	Early tectonic	de Kock & Walraven 1994
Red Granite, zircon,monozite; Goniakontes	U-Pb	534±7	Syn-metamorphic anatexis	Briueu et al. 1980
Kibaran granitoid gneiss,zircon rim Khan R	U-Pb Shrimp	571±64	Damaran metam overprint	Kroner et al. 1991
Kibaran granitoid gneiss,zircon cores Khan R	U-Pb Shrimp	1038±58	Crystallisation of basement granite	Kroner et al. 1991

Table 2: Reliable age dates from the Central Belt of the Damara Orogen. Rb-Sr whole rock isochrons and errorchrons have not been included in this summary since they can be questioned because of problems of non-equilibration between bulk samples and the effects of partial resetting. Likewise, ages obtained using the U-Pb concordia intercepts of different bulk fractions of non-abraded magnetic zircons are questionable due to combinations of Pb-loss and zircon inheritance and have been omitted.

make up 80% of the outcrop and at Rössing Mine, they contain enough uraninite and betauranophane to be mined for uranium. Identical pegmatitic granite sheets cut the detachment *L-S* tectonites. Nex & Kinnaird (this volume) subdivide these pegmatitic granites into six categories on the basis of texture, petrography and chemistry. The next most common type is a grey, weakly foliated biotite granite: it has not been radiometrically dated but where it cuts strongly deformed *L-S* tectonites in the Detachment, then it has a weak foliation but no lineation.

Below the detachment, the basement is often pervasively invaded by white or red tinted medium-grained unfoliated leucogranite, so much so, that in places basement gneiss appears as rafts. The lack of migmatitic structures within these rafts and the evidence of assimilation at their margins, suggests that the leucogranite originated from well below the present level of crustal exposure. The large amount of this granite indicates a major thermal event in the lower crust/upper mantle. This granite is undated, but being unfoliated it must be post-tectonic and might possibly be related to the pegmatitic granites. Above the detachment, especially in the synclinal keels between the domes, a coarsely porphyritic biotite monzogranite, named the "Salem-type" by Miller (1983), is common. This suite has not been precisely radiometrically dated (512 ± 40 Ma, see Table 2) but the non-tectonic fabrics of the majority of intrusions indicate post-detachment ages. Pegmatitic leucogranites (alaskites) do not cross-cut Salem-type

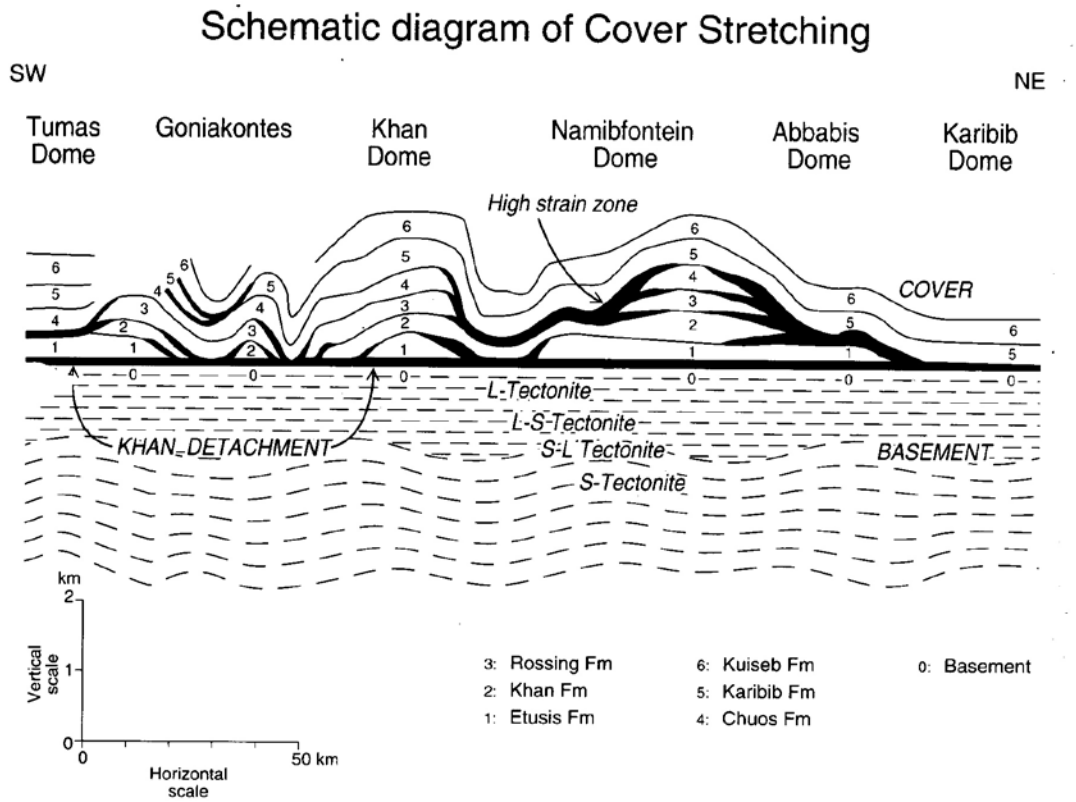

Figure 5: Cartoon of how the cover has been stretched out over the basement following detachment and doming. To simplify the cartoon, the effects of doming have been removed so that the Khan River Detachment is now horizontal. Formation names and distribution of formations taken from Smith (1965). Line of section AA' given on Fig.1. Note the great vertical exaggeration.

granite, so presumably Salem-types are younger than 508 ± 2 Ma (see Table 2). The 505 ± 4 Ma old Donkerhuk granite is homogeneous, late-tectonic and intrudes the boundary between the Central Belt and the Okahandja Lineament Zone (Kukla *et al.*,1991). Similar late- and post-tectonic homogeneous granites intrude the Central Zone itself (see Fig. 1).The large volumes of basement leucogranite, Salem-type and Donkerhuk-type granites (see Fig. 1) suggests important tectonothermal events that affected the Central Zone and its southern boundary (see below).

Stretching of the Cover

Smith's 1965 map of the Central Zone shows that different levels of the Damaran stratigraphy are in contact with the basement in the various domes. This contact is now considered to be a detachment (see above, Oliver 1993, Oliver in press). Twelve different domes have been examined from the Central Zone and as yet no repetition of tectonic slices has been observed. This lack of thrust tectonics (when compared to the Northern and Southern Zones) is taken to be primary evidence that the Khan River detachment is extensional. Fig. 5 is a schematic cross-section (along the line AA' on Fig. 1) which illustrates the effect of stretching the Damaran cover over the basement during the extension of the orogen. The cross section was constructed with the following assumptions: 1) thicknesses of the various Damaran formations, where ever they occur, are assumed to have been the same prior to stretching; 2) where a formation is missing from the section it is assumed to have been so tectonically thinned so as to be unmappable at the scale of Smith's 1965 map (1:100 000); 3) it is assumed that all formations were originally present in the sedimentary sequence across the whole area of the map; 4) for clarity of representation, the folding around the domes has been removed so that the Khan River detachment is now shown as a horizontal surface. Although these assumptions can be criticised it is observed that in the Namibfontein, Khan and Tumas Domes, the Rössing Formation is particularly thinned in places. The impression is that the cover has been plastically stretched and boudinaged on a regional scale. In the field, intensity of foliation and lineation is not only enhanced in the vicinity of the Khan River detachment, but also in other horizons in the cover particularly in fold axes. This topic is presently under further investigation.

Geochronology

Table 2 is a summary of age dates from the Central Zone. Syn-metamorphic granite has been dated at 534 ± 7 Ma in the cover of the Khan Dome (Briqueu *et al.*,1980). "Early tectonic" Okongava diorite from the area of the Otjimbingwe Dome has been dated at 516 ± 6.3 Ma by De Kock and Walraven '(1994) whilst post tectonic doming alaskites (pegmatitic leucogranite sheets) are 508 ± 2 Ma (Briqueu *et al.*, 1980). The late tectonic Donkerhuk granite which intrudes the southern margin of the Central Zone (see Fig. 1), has a concordant U-Pb monazite age of 504 ± 4 Ma (Kukla *et al.*, 1991). Hornblende cooling at 478 ± 4 Ma and muscovite and biotite cooling ages varying between 465-429 Ma (Hawkesworth *et al.*, 1983; Clifford, 1967) indicate exhumation. These results indicate an apparent protracted Damaran tectonometamorphic history of nearly 100 Ma (from 534 to 429 Ma). However, it is still not clear exactly when in the ~100 Ma Damaran history the domes or detachment formed except that they must be pre-alaskite and therefore pre-508 ± 2 Ma and perhaps post-Okongava diorite at 516 ± 6.3 Ma. According to examples reported form the Far East, (Hill *et al.*, 1992), metamorphic core complexes have detached from their covers and unroofed themselves in less than ten million years after initiation in the lower crust.

Metamorphic Core Complex Model

The apparent coincidence of:

1) a regionally extensive detachment zone that can be followed from dome to dome for over 9000 km^2,
2) consistent kinematic indicators for SW directed extensional detachment of the Damaran cover from its basement,
3) a regionally stretched cove(sequence,
4) several phases of regional granite magmatism, both pre- and post-detachment of the cover from the basement,

suggests that the geology can be explained by the metamorphic core complex model (Crittenden *et al.*, 1980; Lister and Davies, 1980). However, as yet a distinct metamorphic discontinuity across the Khan River detachment has not been fully quantified. Oliver (in press) suggested a 100°C gap on the basis of published estimates but proposed caution (new PT work is in progress). Therefore the situation here in Namibia is distinct from the Western Cordillera of the USA where the cover sequence to metamorphic cores is usually weakly metamorphosed and has been detached from its high grade basement first in a plastic and then later in a brittle environment. In Namibia the detachment occurred in the plastic regime whilst the cover was at a high grade of regional metamorphism: this would require thickened cover or a steepened geotherm. One possible scenario is that central Namibia represents the deep seated equivalent of the American situation. Instead of the cover being extended by graben faulting over a stretching plastic basement, the cover was also

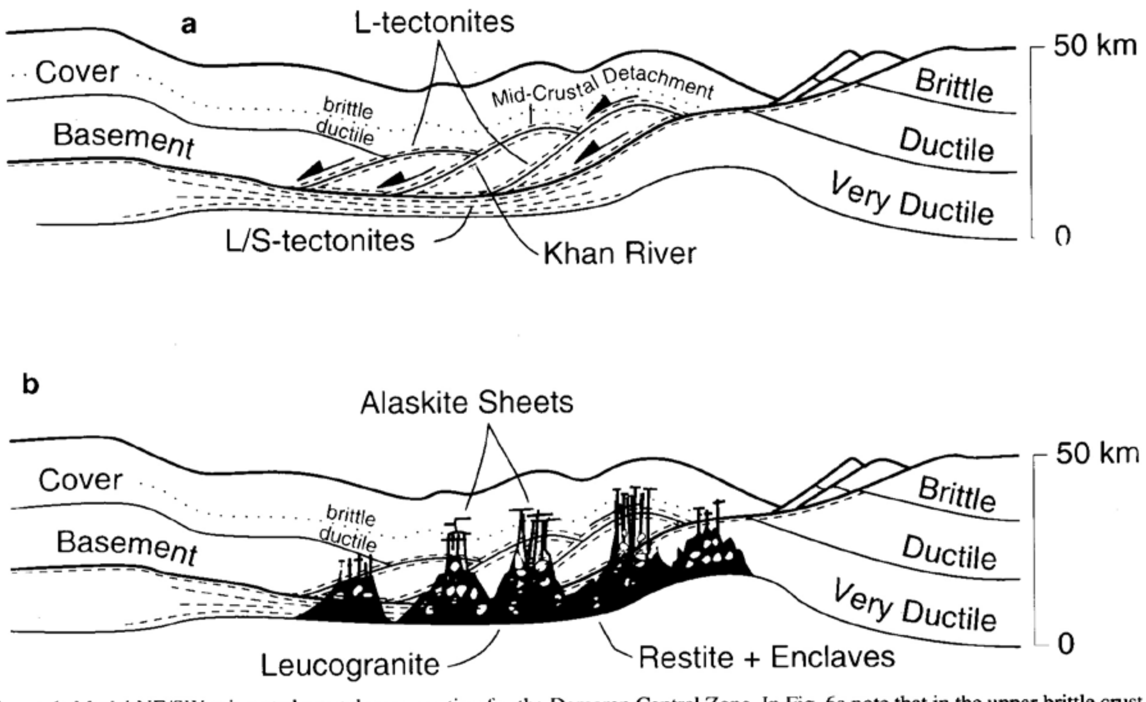

Figure 6: Model NE/SW orientated crustal cross-section for the Damaran Central Zone. In Fig. 6a note that in the upper brittle crust, listric normal faults pass into a ductile extensional shear zone at depth in the middle crust, identified in the Khan River area as the Khan River Detachment. Strain in the middle crust has been inhomogenously partitioned into linked extensional shear zones, focused on the basement-cover detachment; these cut down into the homogeneously stretched very ductile lower crust. Fig. 6b illustrates massive lower crustal melting, caused by the decompression due to crustal extension; some domes are invaded more than others.

plastically stretched. This situation is similar to that described in New Zealand (see Gibson *et al.*, 1989 and Oliver, 1991) and Turkey (see Boskurt and Park, 1994). A cartoon model of the process is presented in Figs. 6a & b which show a NE/SW oriented crustal cross-section for the Central Zone of the Damara. In Fig. 6a note that in the upper brittle crust (not now present in the Central Zone, possibly due to erosion) listric normal faults pass into a ductile extensional shear zone at depth in the middle crust, identified in the Khan River area as the Khan River detachment. Strain in the middle crust has been inhomogenously partitioned into linked extensional shear zones focused on the basement-cover detachment; these cut down into the homogeneously stretched very ductile lower crust. A theoretical extension-decompression mantle melting model has been proposed by McKenzie and Bickle (1988), Pederson & Lo (1992) and applied to the North Sea by Hendrei *et al.* (1993). With either modest or high stretching factors (ß = 1-2.9) and normal or anomalously high values of mantle potential temperatures (ø = 1280-1480°C) either dry or wet biotite-granitic crust below depths of 25 km will be melted (compare the geotherms in Fig. 1 of Pederson & Lo 1992 and Fig. 8 in Hendrie *et al.* 1993 with the granite melting curves presented in Vielzeuf & Holloway 1988.). Fig. 6b illustrates massive lower crustal melting, caused by the decompression due to crustal extension and thinning in the Damara Orogen.

P. Hoffman (pers. comm.) has pointed out that in the absence of thrusting, ductile stretching in the Central Zone cover probably requires an unusually steep geotherm. If such a geotherm is a consequence of NE-SW extension accompanying gravitational collapse, then early brittle extensional structures should be over printed by progressive more ductile structures. Early brittle structures have not been recognised so it *could* be assumed that both the cover and basement were situated at a depth below the brittle/ductile transition (see Fig. 6) at the time of detachment. A high thermal regime *could* have been imposed just prior to the detachment by the influx of granite (see Fig. 6). If the basement-cover detachment is continuous and has no root zone in the area under consideration, then it represents a very long flat (at least 150 km) in the direction of transport. Theoretically, there is no reason why metamorphic core complexes should always break through into the brittle upper crust although the extensional ramp must come up off the flat and rise to the surface somewhere. This ramp has not been recognised in Namibia; it may simply have been eroded away. There ought to be more examples of where the process of exhumation of deep metamorphic core complexes was arrested presumably because extension and orogenic collapse ceased prematurely.

Accurate age dating of central Namibian igneous, tectonic and metamorphic events are needed to test this new hypothesis for deep seated metamorphic core complexes.

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