Reconstruction of important Proterozoic-Cambrian boundary exposures through the recognition of thrust deformation in the Nama Group of southern Namibia

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Northwest-southeast striking northeast-vergent thrust faults divide the exposures of the Kuibis and Schwarzrand Subgroups along the western margin of the Nama basin in southern Namibia into an autochthon and three allochthonous thrust plates. Broad wavelength basement-involved cross-folds create significant structural relief, exposing deep structural levels where the thrust faults merge and pass into basement. These thrust faults are considered to represent late-stage deformation along the leading edge of the Gariep deformational belt.

The Proterozoic-Cambrian boundary, contained within a major unconformity near the top of the Schwarzrand Subgroup, is exposed in each of three thrust plates in the study area. In the lowermost thrust plate, the unconformity lies above a 500 m thick section of the Spitkopf Member, comprising shelf limestone and siliciclastic rocks. Exposures of the Spitkopf Member in the middle and uppermost thrust plates consist of slope facies, are a maximum of 60 m thick and locally are completely eroded by the overlying Proterozoic-Cambrian boundary unconformity. Exposures of the Spitkopf Member in each of the thrust plates are interpreted as geographically widely separated facies on a slope-to-basin transition which is telescoped by the thrust faults into a relatively small area. The total relief along the top of the Spitkopf Member, more than 500 m, is a combination of depositional thinning across the shelf-to-basin transition and erosional incision along the Proterozoic-Cambrian boundary unconformity.

Introduction

This paper describes structural and stratigraphic relationships involving the Vendian to Cambrian Nama Group on Nord Witputs 22, Swartkloofberg 95 and Swartpunt 74 farms in southwestern Namibia (Fig. 1). Exposures of the Nama Group in this area span the Proterozoic-Cambrian boundary. Although the boundary is contained within a major erosional unconformity, U-Pb zircon geochronology on volcanic ash beds, combined with global correlations based on biostratigraphy and carbonisotope chemostratigraphy indicate that the Vendian part of the section extends to within 1 m.y. of the Cambrian System and contains, near its top, some of the youngest known Ediacaran-type fossils (Fig. 2; Grotzinger *et al.*, 1995). Thus, the stratigraphic succession forms an important Proterozoic-Cambrian boundary reference section.

Exposures of the Nama Group in the study area straddle the eastern margin of the contemporaneous Gariep deformational belt (Davies and Coward, 1982; von Veh, 1988). Compressional structures cross-cut the area, resulting in the repetition of stratigraphic units. Fortuitously, the Proterozoic-Cambrian boundary is repeated in three different thrust plates (Fig. 2) which telescope exposures of spatially separate paleogeographic domains into a relatively small and easily accessible region. Here we report results of stratigraphic and structural studies aimed at reconstructing the original succession across the Proterozoic-Cambrian boundary.

General geology

The Nama Group consists of, in ascending order, the Kuibis, Schwarzrand and Fish River Subgroups (Germs, 1983). It was deposited in a foreland basin that subsided in response to convergence along the Damara and Gariep compressional belts (Germs, 1983; Germs and Gresse, 1991) and is deformed along its northern and western margins by compressional structures related to these belts (Martin, 1965; Martin, 1974; Coward, 1983; Miller, 1983). In southwestern Namibia, mixed siliciclastic and carbonate rocks of the Kuibis and Schwarzrand Subgroups thicken southwestward toward the Gariep belt, reaching their maximum thickness (more than 2000 m) in the study area (Figs. 1 & 2).

The Proterozoic-Cambrian boundary, as recognized on the basis of biostratigraphy and carbon-isotope chemostratigraphy, is contained within a regionally extensive erosional unconformity near the top of the Schwarzrand Subgroup (Grotzinger *et al.*, 1995). Ediacaran-type fossils have been discovered in the study area less than 60 m below the unconformity (Grotzinger *et al.*, 1995). In addition, carbon-isotope data from the same Ediacaran fossil bearing section resemble carbon-isotope profiles from terminal Proterozoic sections in Siberia (Pelechaty *et al.*, 1996), arctic Canada (Narbonne *et al.*, 1994), and other areas, reinforcing the terminal Proterozoic age inferred from the biostratigraphy (Fig. 2; Grotzinger *et al.*, 1995). Since typical latest Proterozoic isotope values extend up to the unconformity, with no evidence of the negative isotope excursion which underlies the boundary in other Proterozoic-Cambrian boundary sections, and since the overlying Nomtsas Formation contains Cambrian trace fossils (Germs, 1983; Grotzinger *et al.*, 1995), the Proterozoic-Cambrian boundary is inferred to be contained within the unconformity.

A U-Pb zircon age of 543.3±1 Ma for a volcanic ash bed located 130 m below the Proterozoic-Cambrian boundary unconformity and 90 m below the Ediacaran-type fossils (Fig. 3) is a maximum for the age of the Proterozoic-Cambrian boundary in the study area

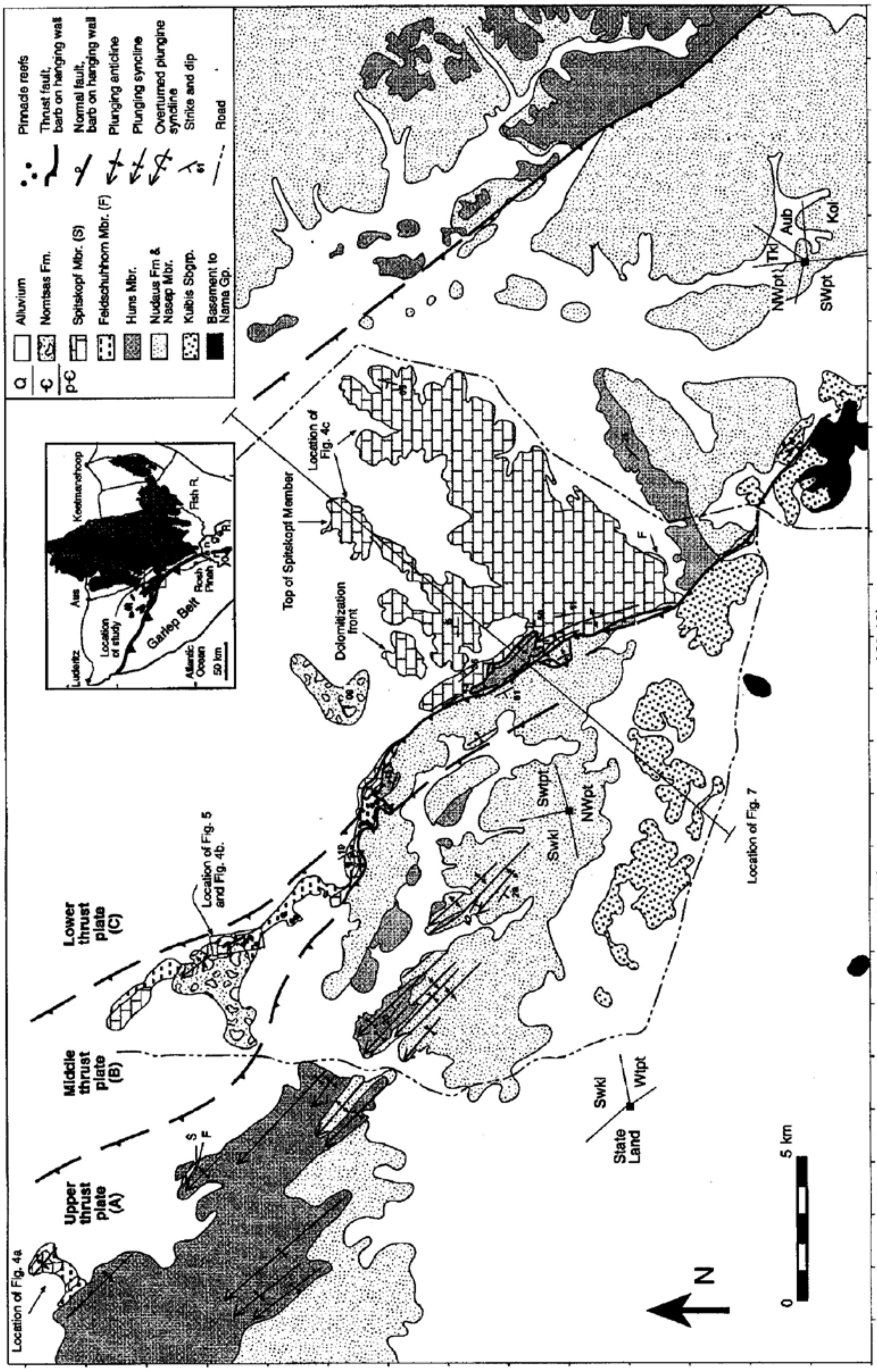

Figure 1: Geological map of the farms Swartkloofberg (Swkl), Swartpunt (Swtpt) and NordWitputs (NWpt). Inset shows location of map area in southwestern Namibia relative to exposures of the Kuibis and Schwarzrand Subgroups (shaded). SWpt: South Witputs; Tkl: Tierkloof; Kol: Kolke

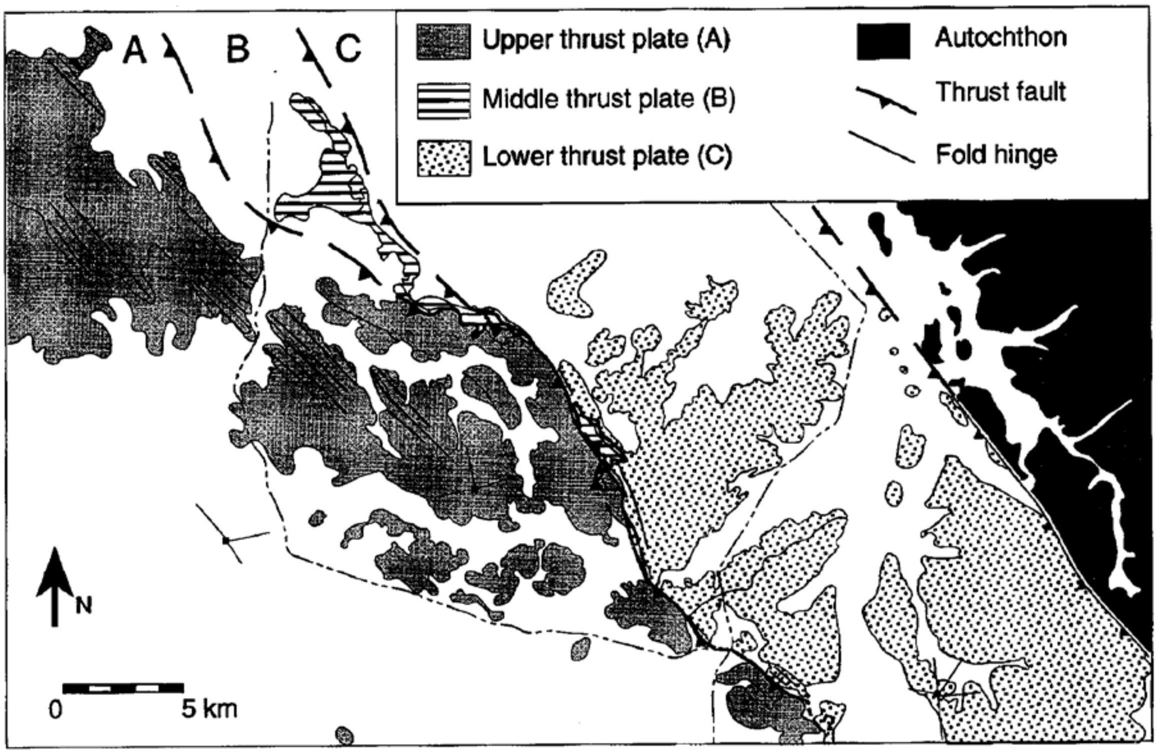

Figure 2: Tectonic map of the study area showing the autochthon and the three thrust plates.

(Grotzinger *et al.*, 1995). This age is the same, within the limits of analytical error, as the age of lower most Cambrian rocks (543.8+5.1/-1.3) in Siberia (Bowring *et al.*, 1993), making the Ediacaran fossils in the study area some of the youngest known representatives of their kind (Grotzinger *et al.*, 1995). An U-Pb zircon age of 538.8 ± 1 Ma for a volcanic ash bed just above the unconformity is a minimum for the age of the Proterozoic-Cambrian boundary in Namibia and constrains the duration of the unconformity to less than 5 m.y. (Grotzinger *et al.*, 1995).

Stratigraphy

The sedimentology and stratigraphy of the Kuibis and Schwarzrand Subgroups have been described and interpreted elsewhere (Germs, 1983; Saylor, 1993; Saylor *et al.*, 1995), and specifics of the stratigraphy in the study area are only briefly described here. This paper focuses on stratigraphic units near the Proterozoic-Cambrian boundary in the study area and how these units change across each of three thrust plates.

Kuibis Subgroup

Exposures of the Kuibis Subgroup are restricted to the southwestern part of the map area where they form part of the lower and upper thrust plates (Fig. 1). The Kuibis Subgroup overlies local outcrops of unnamed stratigraphic units consisting of older diamictite and cream-coloured dolostone, or non-conformably overlies crystalline basement. It is almost 300 m thick and comprises two units of coarse sandstone (Kanies and Kliphoek Members), and two units of dominantly fine-grained carbonate (Mara and Mooifontein Members) (Saylor, 1993; Saylor *et al.* 1995). The siliciclastic dominated units are interpreted to have formed in fluvial to marine margin environments and the carbonate dominated units in shallow subtidal settings (Germs, 1983; Saylor *et al.*, 1995).

Lower Schwarzrand Subgroup

The lower Schwarzrand Subgroup, comprising the Nudaus Formation and the Nasep Member of the Urusis Formation, crops out across much of the map area (Fig. 1). It is 400 m thick and is dominated by siliciclastic mudstone and sandstone, interpreted to have formed in mid-shelf to nearshore and deltaic environments (Germs, 1983; Saylor, 1995). The Nudaus Formation is 150 m thick and consists of sandier-upward parasequences comprising green mudstone with intercalated thin- to medium-bedded sandstone. The upper Nudaus Formation and the lower Nasep Member form a 60 m interval comprising 5 to 20 m-thick units of medium-bedded sandstone, shale and grainstone. The middle 100 m of the Nasep Member consist of green shale, and the upper 60 m consist of cross-bedded and planar laminated, locally slumped, fine sandstone.

Upper Schwarzrand Subgroup

The middle part of the Schwarzrand Subgroup, comprising the Huns, Feldschuhhorn and Spitkopf Members of the Urusis Formation, is interpreted as a carbonate ramp succession (Saylor *et al.*, 1995). It reaches a total thickness in the study area of nearly a kilometre. The Proterozoic-Cambrian boundary unconformity lies at the top of the Spitkopf Member and cuts down section, so that the overlying Cambrian Nomtsas Formation rests on progressively lower strata of the Spitkopf, Feldschuhhorn and Huns Members. The details of this erosional incision and facies and thickness changes in the underlying carbonate platform are pieced together here from structurally and geographically isolated outcrops in each of the three thrust plates.

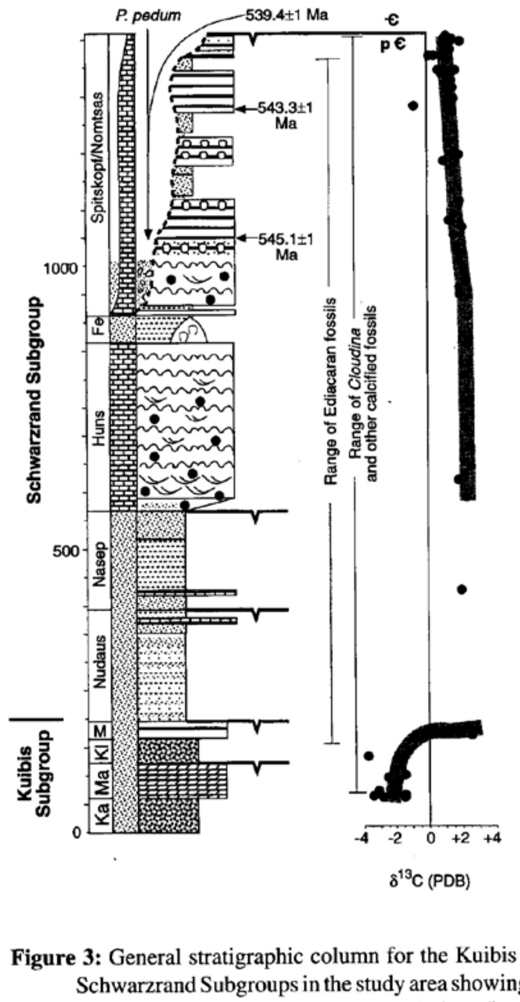

Figure 3: General stratigraphic column for the Kuibis and Schwarzrand Subgroups in the study area showing U-Pb zircon ages and carbon-isotope variations (isotope data from Saylor *et al.* in press; radiometric ages from Grotzinger *et al.*, 1995). See Figure 4 for key. Ka: Kanies Member; Ma: Mara Member; Kl: Kliphoek Member; M: Mooifontein Member.

Huns Member

The Huns Member is a nearly 300 m thick unit consisting predominantly of limestone. The basal 40 m of the Huns Member is recessive, comprising shale with limestone and sandstone interbeds. The remainder consists of metre-scale, upward-shallowing cycles. The few siliciclastic units correlatable across the study area never exceed a few metres in thickness. The carbonate cycles comprise elongate, dolomitized columnar stromatolites overlain by upward-coarsening cross-stratified pellet and intraclast grainstone and commonly are capped by karst-surfaces. They are interpreted to have formed in a high-energy, wave-swept shoal area strongly influenced by high frequency relative sea-level oscillations (Saylor *et al.*, 1995). A unit of pink lime mudstone, with metre high thrombolitic and stromatolitic columns and domes, and intercalated green shale forms the top of the Huns Member. This distinctive unit is recognizable and correlatable across the map area (Fig. 4).

Reefs

Exhumed pinnacle reefs are preserved in the middle thrust plate (Figs. 1, 3 and 4). Initially these reefs were interpreted as part of the Cambrian Nomtsas Formation and were thought to have grown in an erosional valley that incised through the Spitkopf Member (Germs, 1983). However, they lie above light-coloured stromatolitic limestone similar to that at the top of the Huns Member and locally lie below dark, thin-bedded Spitkopf limestone. Consequently, they have been reinterpreted as part of the Huns Member (Figs. 3 & 4; Saylor, 1993; Saylor *et al.*, 1995)

In one location (Fig. 5; see Fig. 1 for location) two pinnacle reefs are enveloped in shale and conglomerate of the Cambrian Nomtsas Formation. They appear to project from a layer of stromatolitic limestone, which itself appears to abut Spitkopf limestone along the steep wall of an incised valley. However, the juxtaposition against the valley wall is not stratigraphic. Instead, it is the result of a small normal fault with only a few metres of offset. The distinctive stromatolitic layer can be recognized on both sides of the normal fault and can be traced laterally in the hanging wall to where it is enveloped in siliciclastic mudstone of the Feldschuhhorn Member and underlies dark limestone of the Spitkopf Member. The surface layer of the pinnacle reefs at this level resembles the stromatolitic layer suggesting that mantling of the lower pinnacles by the stromatolitic layer can account for what appears to be two different reef horizons. Much like their present exposure, the reefs most likely formed resistant structures that were exhumed from surrounding shale during canyon incision. The reefs were covered again with conglomerate as the canyon filled with Nomtsas Formation.

In summary, nowhere do the stratigraphic relationships require that any of the pinnacle reefs lie within the Nomtsas Formation (Saylor *et al.*, 1995). In contrast, they are all considered to have developed from a single horizon at the top of the Huns Member during a period of reduced carbonate production following flooding and drowning of the platform.

Feldschuhhorn Member

The Feldschuhhorn Member is a 60 m thick green-shale unit. It stratigraphically overlies and envelopes the pink stromatolitic limestone and pinnacle reefs at the top of the Huns Member (Figs. 1, 3, 5). Locally developed, light-coloured stromatolitic limestone is interpreted above to mantle the pinnacle reefs. The upper part of the Feldschuhhorn Member contains interbedded sandstone and grades upward into black, fine-grained limestone of the Spitkopf Member.

Spitkopf Member

The Spitkopf Member in the lower thrust plate has not previously been described in any detail. It is 500 m thick (Fig. 4c) and consists of alternating carbonate and siliciclastic units, each of which is several tens to one hundred or more metres thick. The lower carbonate units consist largely of metre-scale, karst-capped cycles, which, similar to cycles of the Huns Member, are interpreted to have formed in a high-energy wave-swept environment. Higher carbonate units consist of thin-bedded, fine-grained limestone with local development of thrombolitic and stromatolitic domes and the upper carbonate units consist almost entirely of thick-laminated to thin-bedded limestone with rare beds of flat-pebble, intraclast breccia, commonly with mounded tops. With the exception of intraclast breccias, which are interpreted to have formed during occasional storms, which ripped-up and reworked the thinbedded limestone (e.g. Sepkoski, 1982), higher carbonate units show little evidence for the influence of strong waves or currents. They resemble Cambrian "ribbon-rock" and are similarly interpreted to have formed in low-energy, shallow- to deeper-subtidal environments on a carbonate ramp (Demicco, 1983; Cowan and James, 1993). Thick siliciclastic units form coarsening-upward successions, each with green mudstone at the base followed by ripple-laminated or thick-bedded, planar-laminated and hummocky cross-stratified very fine to fine sandstone at the top. These siliciclastic facies are interpreted to have been deposited in outer- to mid-shelf environments.

The Spitkopf Member in the middle and upper thrust plates (Figs 4a, b) is less than 60 m thick. It consists of fine-grained, black, thick-laminated to thin-bedded limestone, breccia and shale. The breccia beds are composed of platy clasts that resemble the surrounding limestone. Breccias range from incipient fracture zones, to fully-developed, matrix-supported, disorganized debrites. The relative proportion of breccia, particularly debrites, and shale increases westward. These sections of the Spitkopf Formation resemble the Cow Head Formation of Newfoundland (e.g. James and Mountjoy, 1983) and are interpreted to have formed by slope failure and mass-wasting on a carbonate slope.

The combination of ramp- and slope-type facies that constitutes the Spitkopf Member is characteristic of distally steepened ramps (Read, 1985). Exposures of the Spitkopf Member in the study area are interpreted as representative sections along a ramp to basin transition, extending from outer ramp to slope positions (e.g. James and Mountjoy, 1983), which have been structurally telescoped into a relatively small area.

Nomtsas Formation

Exposures of the Nomtsas Formation are restricted to the northern part of the map area. They overlie and form the fill of erosional canyons incised through the Spitkopf Member.

Outcrops of this Formation in the lower thrust plate are inferred to overlie the Spitkopf Member, but the contact is covered. Exposures of the stratigraphically underlying Spitkopf Member near the covered zone are dolomitized and brecciated. The dolomitization and brecciation are local features, however, and this horizon can be traced laterally to undeformed limestone approximately 120 m below the top of the SpitkopfMember (see Fig. 1). It is unclear whether the Nomtsas Formation lies directly on this dolomitized horizon, or if the remaining 120 m of the section are buried beneath intervening Quaternary alluvium. However, based on the similarity of this horizon to a dolomitized and brecciated unit which directly underlies exposures of the Nomtsas Formation in the middle thrust plate, we suggest that it may correspond to the Spitkopf-Nomtsas contact and that the basal erosion surface of the Nomtsas Formation in the lower thrust plate may have cut down into as much as 120 m of the Spitkopf Member (Fig. 4c).

In the middle structural unit, the Nomtsas Formation overlies a 60 m thick section of the Spitkopf Member and locally the basal erosion surface has cut entirely through the Member down to the level of pinnacle reefs at the top of the Huns Member (Fig. 4b). Stromatolitic and thrombolitic carbonate at the top of the Spitkopf exposures and immediately underlying the Nomtsas Formation is dolomitized and characterized by extensive development of fitted breccias.

Nomtsas rocks in the middle and upper thrust plate are lithologically and stratigraphically similar comprising matrix- and clast-supported conglomerate, overlain by shale-rich diamictite, followed by clast-free mudstone with interbedded sandstone. Disorganized and locally inverse-stratified boulder and pebble conglomerate in a sandy matrix and shale-rich diamictite with outsized clasts as large as 3 m across are interpreted to have formed by debris-flow and slump processes (Saylor, 1993; Saylor *et al.*, 1995). Conglomerate clasts, which include limestone, dolostone, sandstone and volcanic ash, are lithologically similar to stratigraphically lower units and are interpreted as debris shed from the flanks of incised valleys (Saylor, 1993; Saylor *et al.*, 1995). Clasts similar to the dolomitized unconformity

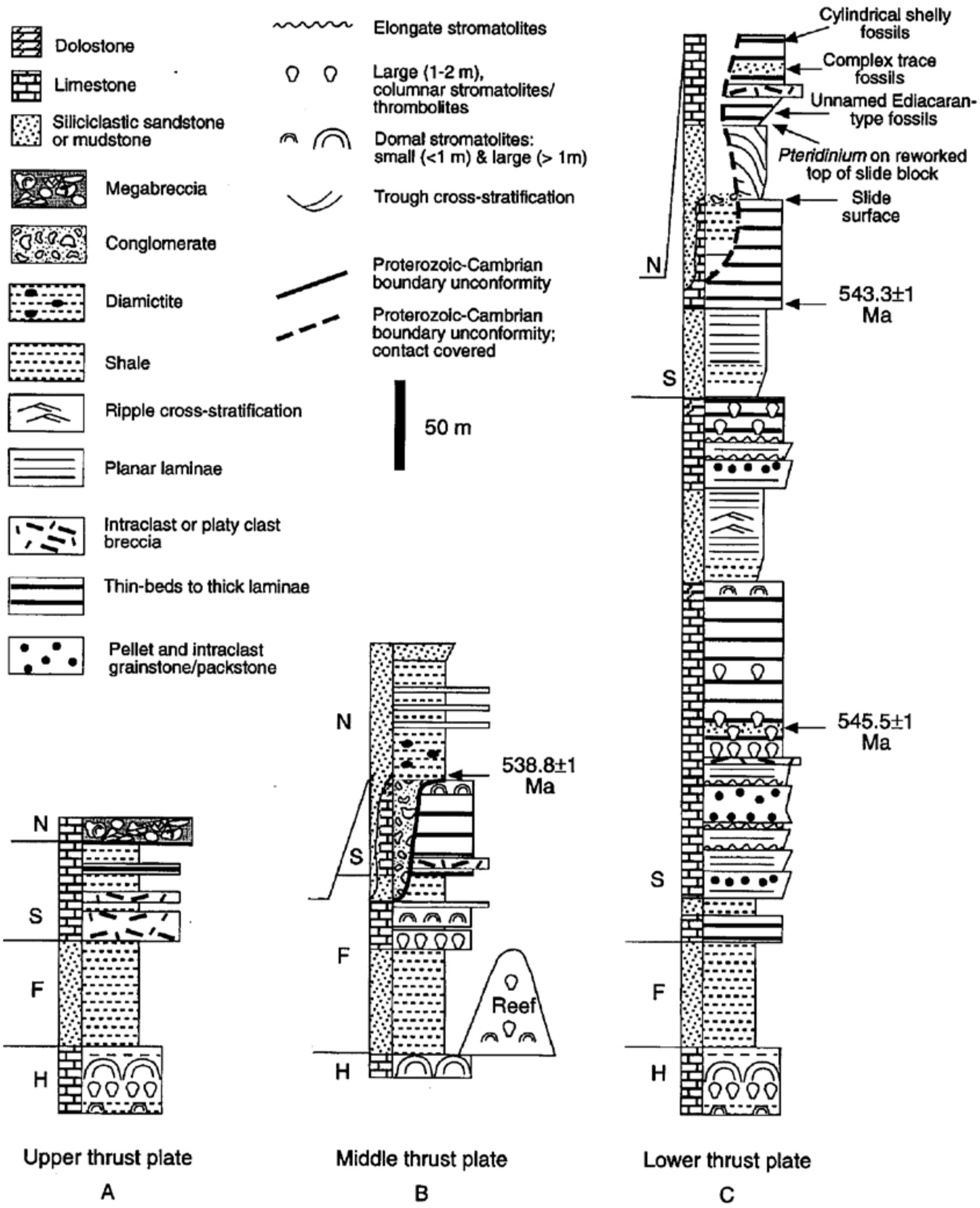

Figure 4: Measured sections from the top of the Huns Member (a distinctive pink stromatolitic unit) up to the Nomtsas Formation for the lower, middle and upper thust plates. See Fig. 1 for locations of sections. H: Huns Member; F: Feldschuhhorn Member; S: Spitkopf Member: N: Nomtsas Formation.

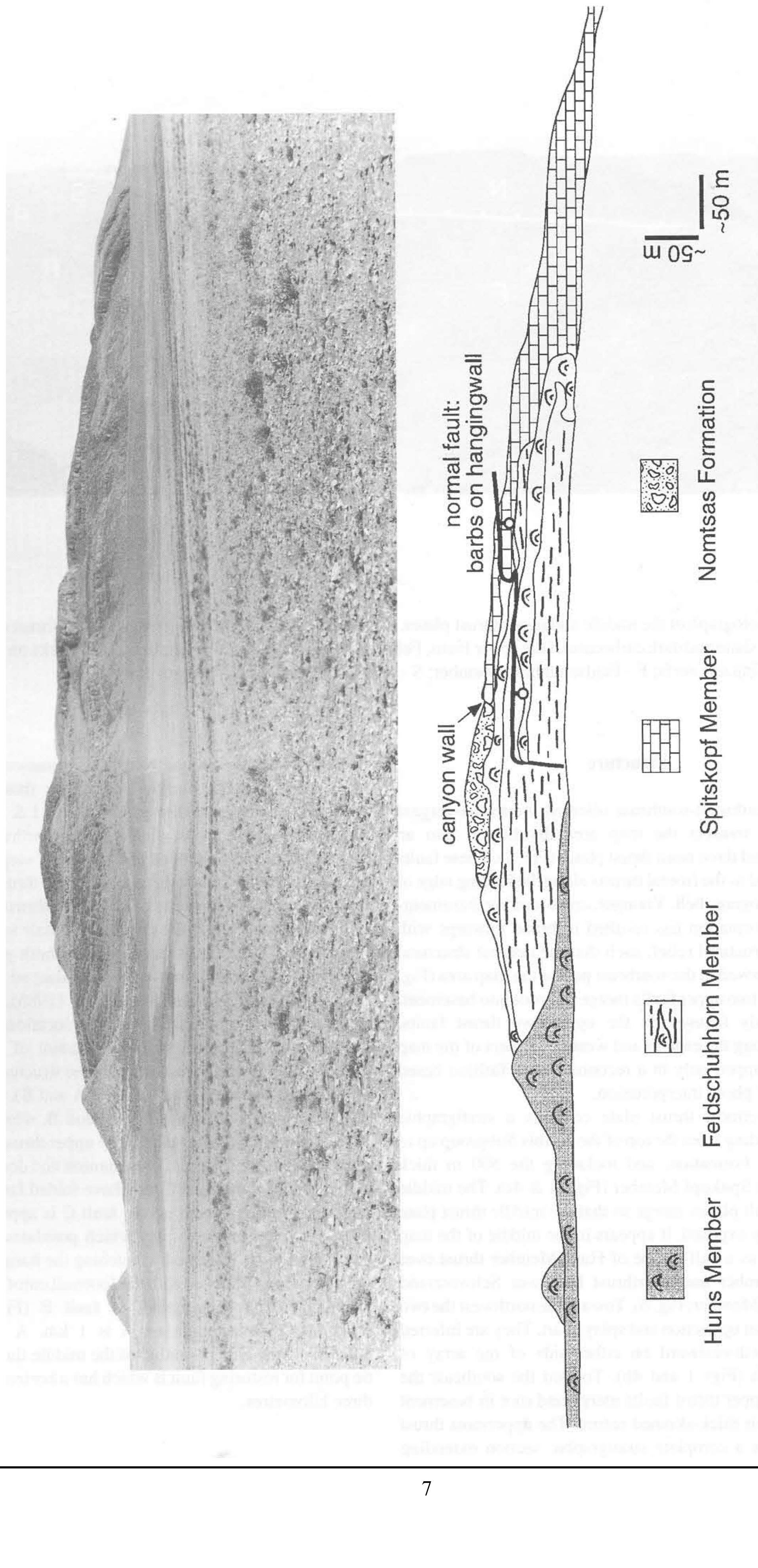

Figure 5: Line drawing and photograph of structural and stratigraphic relationships involving pinnacle reefs on the farm Swartkloofberg . See text for discussion and Fig. 1 for location.

Figure 6: Photograph of the middle and upper thrust plates. Siliciclastic rocks of the Nasep Member are thrust over pinnacle reefs, shale and dark carbonate of the upper Huns, Feldschuhhorn and Spitskop Members. Tick marks on hangingwall. (R - pinnacle reefs; F - Feldschuhhorn Member; S - Spitskop Member; N - Nudaus Formation)

surface may indicate that dolomitization preceded valley infilling.

In the western part of the map area the surface corresponding to the sub-Nomtsas unconformity may be represented by an abrupt change in conglomerate facies from SpitkopfMember slope breccia, composed of platey clasts of deep water slope-facies limestone, to megabreccia with large (up to 3 m) boulders of stromatolitic, thrombolitic and massive fine-grained dolostone and limestone similar to the more shallow-water ramp facies (Fig. 4a). Slope breccias on distally steepened ramps such as the Spitkopf Member generally consist entirely of deep-water clasts (James and Mountjoy, 1983). Thus, although the megabreccia has no sand in the matrix and differs from other exposures of the Nomtsas Formation conglomerate, the change to more shallow-water clasts probably records shelf-edge exposure and erosion (e.g. Hiscott and James, 1984) during relative sea-level fall and the initial development of the up-dip, sub-Nomtsas unconformity.

Structure

Three northwest-southeast oriented, northeast - vergent thrust faults transect the map area dividing it into an autochthon and three main thrust plates (Fig. 2). These faults are interpreted as the frontal thrusts along the leading edge of the Gariep orogenic belt. Younger, cross-cutting, basement-involved deformation has resulted in broad upwarps with significant structural relief, such that the deepest structural levels are exposed in the southeast part of the map area (Fig. 1), where the two upper faults merge and root into basement.

This study focuses on the upper two thrust faults. Structures along the eastern and western borders of the map area were mapped only in a reconnaissance fashion based largely on air photo interpretation.

The lower most thrust plate contains a stratigraphic section extending from the top of the Kuibis Subgroup up to the Nomtsas Formation, and including the 500 m thick section of the Spitkopf Member (Figs. 1 & 4c). The middle and upper fault planes merge so that the middle thrust plate is only locally exposed. It appears in the middle of the map area (Fig. 1) as a half-klippe of Huns Member thrust over Spitkopf Member and overthrust by lower Schwarzrand rocks (Nasep Member; Fig. 6). Toward the northwest the two thrust faults cut up section and splay apart. They are inferred to extend northwestward on either side of the array of pinnacle reefs (Figs. 1 and 4b). Toward the southeast the middle and upper thrust faults merge and root in basement indicating their thick-skinned nature. The uppermost thrust plate contains a complete stratigraphic section extending from basement up into the Nomtsas Formation (Fig. 4a).

Rocks in the middle and upper thrust plate are deformed by numerous linked folds (Figs. 1 & 2). The folds parallel the thrust faults, plunge to the northwest, and are generally open, but inclined and northeast-vergent. Locally the folds are isoclinal or are cut by minor thrust faults with displacement of a few metres. The middle thrust fault itself is folded. Deformation in the lower thrust plate is less intense. Near the bounding faults there are a few fault-parallel folds.

Figure 7 shows a cross-section, balanced according to the principles of explained by Suppe (1983), through the middle of the map area (see figure 1 for location). This cross-section meets the stratigraphic constraint of successively more distal exposures westward and the structural constraint of merging, basement rooted faults (A and B).

The oldest fault in the area is fault B, which forms the base of the middle thrust plate. The upper thrust plate lies in a splay (fault A) of fault B. Later motion and development of a thrust ramp along fault C may have folded faults A and B. Horizontal displacement across fault C is approximately 1 km. Since fault A is a splay which postdates fault B, the offset along A is restored by matching the hanging wall cut-off of the Huns Member with the footwall cutoff of the Huns Member in the hanging wall of fault B (Fig. 7b). The horizontal displacement on A is 1 km. A hanging wall anticline in the Huns Member of the middle thrust plate is a tie point for restoring fault B which has a horizontal offset of three kilometres.

Paleogeographic restoration

The stratigraphic succession from the Kuibis Subgroup up through the Huns Member of the Schwarzrand Subgroup shows little change across the three thrust plates. Thicknesses remain approximately the same and distinct beds and marker horizons can be recognized across the map area. The SpitkopfMember, however, changes significantly. In the lower thrust plate it is 500 m thick, but in the middle and upper thrust plates it is 0 to 60 m thick. In the lower thrust plate the Spitkopf Member consists of outer ramp limestone and deltaic sandstone, and in the upper two thrust plates it consists of deeper-water limestone, breccia and shale on a distally steepened ramp.

These substantial differences are not the result of modern erosion patterns because in all thrust plates contacts with the underlying Feldschuhhorn Member and the overlying Nomtsas Formation are preserved. Instead, these differences reflect some combination of stratigraphic thinning and facies change, across the distal ramp and erosional truncation on a basin ward-dipping unconformity beneath the Nomtsas Formation (Fig. 8). The pattern of erosional modification of original depositional relief is similar to relationships described from the shelf margin of the Permian Grayburg Formation in west Texas (Franseen, 1989).

The total amount of relief along the top of the Spitkopf Member, 500 m over a palinspastically restored distance of 8 km, is similar in scale to, although somewhat greater than the relief across the Grayburg shelf margin (350 mover 4.5 km). Over a distance of 5 km in the lower thrust plate there may be as much as 130 m of erosional incision on the sub-Nomtsas unconformity. In the middle thrust plate, there is at least 60 m of incision expressed by the steep walls of the unconformity surface (Fig. 4 b, c). Consequently, the remaining 310m of relief must be accounted for over the distance (3 km) represented by the horizontal displacement of the lower thrust fault.

There is essentially no depositional thinning in the upper thrust plate and most of the shelf-to-basin tran-

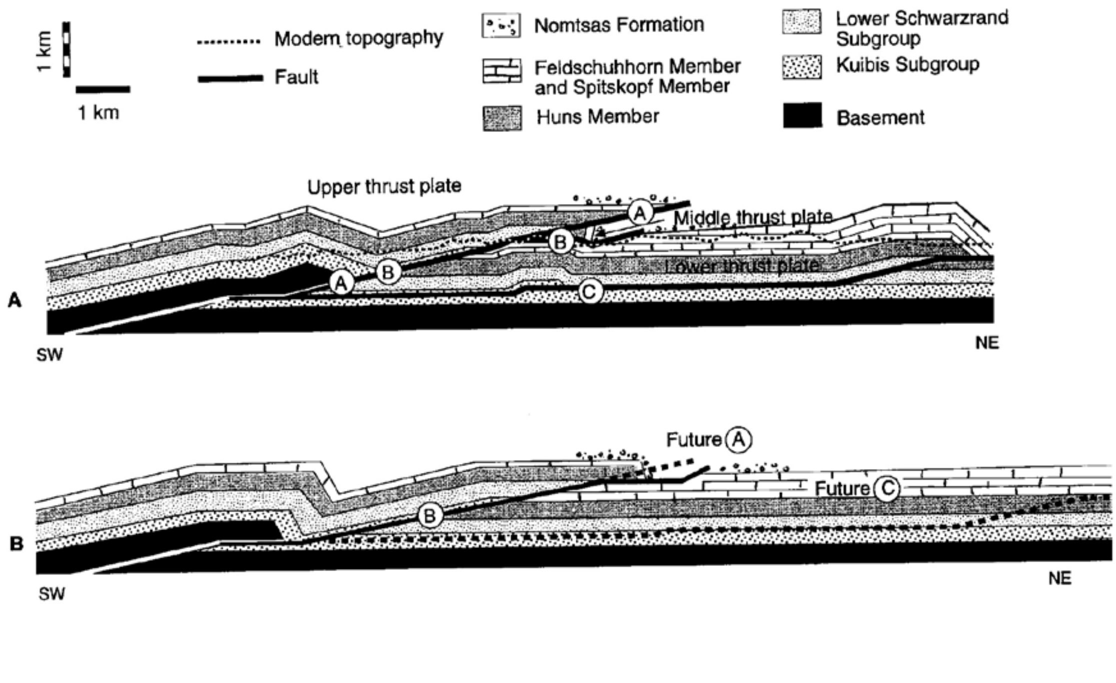

Figure 7: a. Cross-section showing the lower, middle and upper thrust plates. Location of cross-section shown in figure 1. **b.** Partially restored cross-section showing geometry prior to movement along fault C and splay A. Note that the lower Schwarzrand Subgroup includes the Nudaus Formation and the Nasep Member.

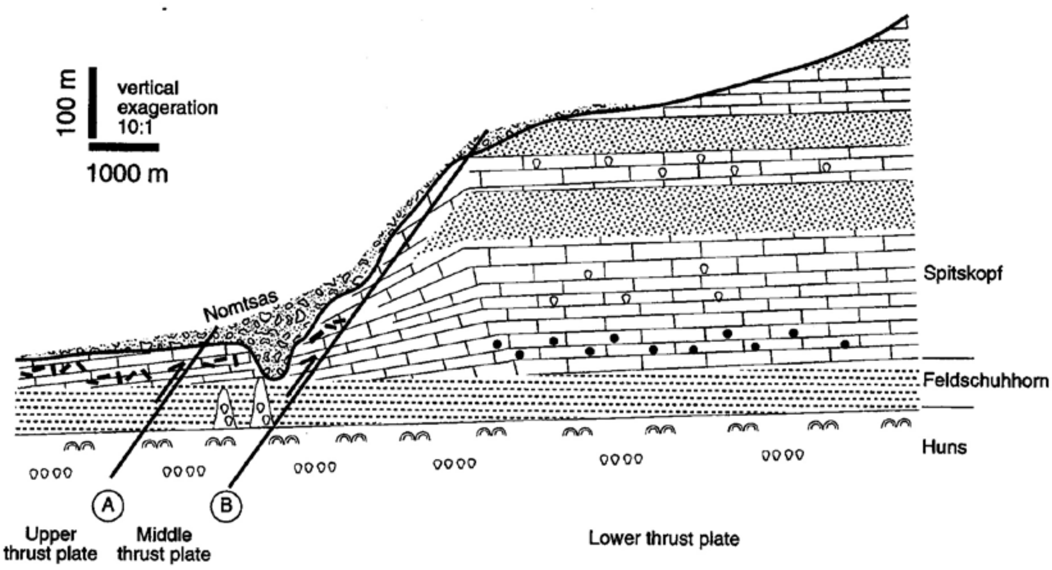

Figure 8: Schematic cross-section through the shelf-to-basin transition of the Spitskopf Member. The total relief along the Precambrian-Cambrian boundary, which is shown by the thick, solid line, is a combination of depositional thinning and erosional truncation of a distally steepened ramp Key in Fig. 1.

sition has been cut out along the middle thrust fault. Since no marker horizons in the Spitkopf Member can be correlated across this fault, the proportion of the 310m of relief which is represented by pre-erosion depositional thinning across the shelf-to-basin transition is unknown. The calculated depositional slope for the maximum possible amount of depositional thinning, (310 m across the palinspastically restored distance of 3.5) is 6°. Although somewhat high, 6° is reasonable for the distally steepened part of a ramp and is consistent with the abundance of breccias in the slope sections (Read, 1985). The original depositional profile may have been much less steeply inclined, however, because slopes of only 2° are sufficient to cause slope failure. Since erosional incision affected both ramp exposures in the lower thrust plate and slope exposures in the middle thrust plate, incision and the relief along the erosional escarpment probably modified the depositional ramp profile substantially.

It is uncertain whether the erosional relief across the distally steepend ramp developed everywhere by sub-aerial exposure and fluvial incision or, if, like the Grayburg escarpment, some parts, particularly those down-dip, developed by submarine erosion and mass wasting. The unconformity surface is recognized 100 km east (cratonward) of the study area where it is associated with incised canyons a few tens of metres deep. There, the canyons are partially infilled by planar-stratified conglomerate and trough cross-stratified sandstone (unpublished data), facies which record strong current influence. The great lateral extent of erosional topography developed along this unconformity surface and the evidence for strong currents are hard to account for by mass wasting in an exclusively sub-marine environment, so the more proximal canyons are tentatively interpreted to have formed by fluvial incision. A striking similarity between facies of the Nomtsas Formation in each of the thrust plates, with no apparent change in environment, is suggestive of deposition during diachronous transgression and back -filling of the escarpment, following a large relative sea-level drop. The coarse conglomerate and diamictite facies consists of debris derived from the escarpment and deposited by sediment gravity flows, probably in a deeper marine environment consistent with the preceding slope setting. Fine conglomerate and sandstone facies may have been introduced by mass wasting of facies derived from up-slope estuarine environments (Saylor *et al.*, 1995). Dolomitization fronts and mantling breccias associated with the unconformity in both the lower and middle thrust plates in the study area may have been formed by mixing of meteoric and marine waters following exposure and karst weathering (e.g. Badiozamani, 1973; James and Choquette, 1987), but may also have been formed much later by fluids that travelled through the porous Nomtsas Formation (e.g. Mussman *et al.*, 1987). Support for early (pre-Nomtsas) dolomitization is provided by the presence of dolomitized clasts within the Nomtsas Formation.

The Proterozoic-Cambrian boundary unconformity is therefore interpreted to record a major fall in relative sealevel. A minimum estimate for drop in relative sea-level is a few tens of metres, sufficient to expose and incise up-dip portions of the unconformity. If dolomitization along down-dip exposures of the unconformity surface is related to karst processes, relative sea-level fall might have been 500 m or more.

The Nama basin was a tectonically active foreland basin (Germs, 1983) and tectonic uplift associated with thrust deformation may have been an important factor in the development of the erosional unconformity. Stratigraphic patterns throughout the Schwarzrand Subgroup, including westward-thickening stratigraphic units and eastward downcutting erosional unconformities, indicate tectonically driven flexural subsidence of the western part of the basin and slower subsidence and episodic uplift of the eastern part of the basin (Germs and Gresse, 1991; Gresse and Germs, 1993; Saylor *et al.*, 1995). Certainly erosion along the eastern extent of the Proterozoic-Cambrian boundary unconformity surface may be related to uplift of a flexural bulge (Germs and Gresse, 1991). Evidence for rapid subsidence of the western part of the basin, however, indicates that it lies in front of the bulge and that development of the unconformity in the study area cannot be explained by bulge uplift. The coincident development of an erosional unconformity in both the rapidly subsiding western part of the basin and the slowly subsiding eastern part of the basin may best be explained by a eustatic sea-level fall. The recognition of approximately coeval unconformities at the Proterozoic-Cambrian boundary in Siberia (Pelechaty *et al.*, 1996), Canada (Narbonne *et al.*, 1994) and the western United States (Cooper and Fedo, 1995) demonstrates the global nature of this unconformity and provides additional evidence that the sea-level fall may be eustatic in nature (Runnegar *et al.*, 1995).

Conclusions

1) Northwest-southeast striking thrust faults divide exposures of the Kuibis and Schwarzrand Subgroups on the farms Swartkloofberg, Swartpunt, Nord Witputs, Tierkloof and Aub into an autochthon and three thrust plates. The thrust faults root into base-ment and are interpreted as the leading edge of the Gariep deformational belt. The Proterozoic-Cambrian boundary, contained within a major unconformity in the upper part of the Schwarzrand Subgroup, is exposed in each of the thrust plates.
2) The lower thrust plate contains a nearly complete stratigraphic section extending from the top of the Kuibis Subgroup up to the Cambrian Nomtsas Formation at the top of the Schwarzrand Subgroup. The unconformity at the base of the Nomtsas formation lies above a 500 m thick section of the Spitkopf Member and has erosional relief of more than 130 m.
3) The middle thrust plate contains only the middle and upper part of the Schwarzrand Subgroup. Pinnacle reefs are restricted to the middle thrust plate. The reefs lie structurally above the upper Spitkopf Member and were originally misinterpreted as part of the Nomtsas Formation, but have been reinterpreted to lie stratigraphically at the top of the Huns Member. Exposures of the Spitkopf Member above the pinnacle reefs in the middle structural level are a maximum of 60m thick and locally the Proterozoic-Cambrian unconformity cuts down to the level of the reefs.
4) The upper thrust plate contains a complete section from basement up to conglomerate thought to correlate with the sub-Nomtsas unconformity. The SpitkopfMember is a maximum of 60 m thick and consists of toe of slope facies.
5) The character of the SpitkopfMember changes across the structural levels from distal ramp to slope facies. These facies formed along a ramp-to-basin transition which was dissected by thrust faults and telescoped into a relatively small area. The total relief along the Proterozoic-Cambrian unconformity, more than 500 m, is a combination of depositional thinning and erosional incision across this transition.
6) The Proterozoic-Cambrian boundary unconformity in Namibia developed during a major fall in relative sealevel. Development of significant erosional topography along the down-dip exposures of the unconformity surface, well in front of the flexural bulge, may be explained best by a eustatic sea-level fall. This interpretation is strongly supported by Runnegar *et al.*'s (1995) suggestion that approximately coeval falls in relative sea-level in Siberia, Canada and the western United States indicate a eustatic sea level event at this time.

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