

Proterozoic–Paleozoic Sedimentary Rocks and Mesozoic–Cenozoic Landscapes of the Cape Mountains Across the Kango Complex Reveal ‘More Gaps Than Record’ from Rodinia and Gondwana to Africa

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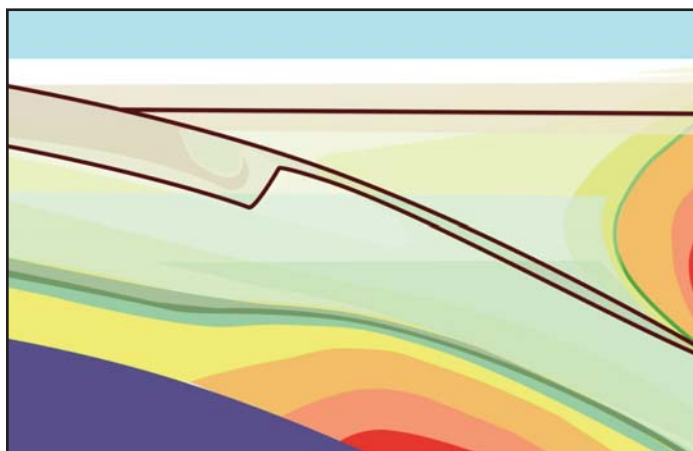
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Résumé de l'article

La région du Kango (Cango) flanque les marges nord du petit Karoo et des montagnes du Cap dans la province du Western Cape en Afrique du Sud. Elle préserve une stratigraphie condensée protérozoïque–paléozoïque exposée via une morphologie mésozoïque–cénozoïque avec une topographie actuelle de type alpin. Ses roches et ses paysages ont été cartographiés et documentés durant les 150 dernières années. Au cours des 25 dernières années, nous avons re-cartographié et daté une section du centre-est de cette région. Les roches litées de manière subverticale et clivées révèlent une stratigraphie de 8 à 10 km d'épaisseur couvrant plus de 700 millions d'années entre environ 1200 et 500 Ma avec plusieurs non-conformités et disconformités. À 252 Ma, au cours de l'orogénèse du Cap, ce Complexe du Kango s'est déformé le long de chevauchements et de plis isoclinaux produisant des schistes à fort pendage. Il a été soulevé de 3 à 5 km au cours de l'épirogenèse du Kalahari entre 140 et 60 Ma, tout en s'érodant à 100–200 m/m.a. (120–80 Ma). Pendant le Cénozoïque, le taux de soulèvement a diminué d'un ordre de grandeur et il est aujourd'hui d'environ 0,4 à 0,7 m/m.a. à travers des pentes abruptes et des canyons, contrairement à l'Himalaya où les taux d'érosion sont environ cent fois plus rapides. Une publication récente sur cette section du centre-est de la région du Kango conteste l'existence de plis isoclinaux régionaux et suggère que le dépôt des plus anciennes successions sédimentaires, y compris les roches carbonatées des Grottes du Cango (marbre calcaire avec des microfossiles énigmatiques) était simple, continu et limité entre environ 700 et 500 Ma, diminuant les estimations antérieures de la tranche d'âge stratigraphique de 60–80%. De même, des interprétations récentes des paysages complexes relient le contact nord entre les séquences rocheuses du Kango et de Table Mountain à des failles quaternaires. Nous présentons une nouvelle base de données géologiques, cartographiée à des échelles entre 1:500 et 1:10,000, et douze coupes stratigraphiques avec des directions de superposition liées à des données structurales et isotopiques qui concordent avec les répétitions le long des plis isoclinaux régionaux et des zones de chevauchement des séquences du Kango pendant l'orogénèse permo-triassique du Cap, et des données géomorphiques qui relient l'origine de ses paysages à l'altération et à l'érosion au cours de l'épirogenèse du Kalahari au Crétacé–Cénozoïque. Au cours de son évolution, le bassin du Kango flanquait les systèmes montagneux grenvillien et panafricain. Mais, à un taux de sédimentation moyen d'environ 1 mm/70 ans (0,014 mm/an) et avec les faibles taux d'érosion actuels (0,005 mm/an), il manque probablement plus d'enregistrements de la tectonique et érosion de ces différentes régions de Rodinia et Gondwana avant l'émergence de l'Afrique que ce qui est actuellement préservé. Pour évaluer la signification géodynamique de ces intervalles de temps manquant, il faut d'avantage de cartographie de terrain associée à de nouvelles géosciences transdisciplinaires.

ANDREW HYNES SERIES: TECTONIC PROCESSES



Proterozoic–Paleozoic Sedimentary Rocks and Mesozoic–Cenozoic Landscapes of the Cape Mountains Across the Kango Complex Reveal ‘More Gaps Than Record’ from Rodinia and Gondwana to Africa

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SUMMARY

The Kango (Cango) region flanks the northern margins of the Klein Karoo and the Cape Mountains across the Western Cape Province of South Africa. It preserves a condensed Proterozoic–Paleozoic stratigraphy exposed via a Mesozoic–Cenozoic morphology with a present Alpine-like topography. Its rocks and landscapes have been repeatedly mapped and documented for the past 150 years. Over the last 25 years, we remapped and dated a central-eastern section of this region. The subvertically bedded and cleaved rocks reveal an 8–10 km thick stratigraphy

covering more than 700 million years between ca. 1200 and 500 Ma with several unconformities and disconformities. At ca. 252 Ma, during the Cape orogeny, this Kango Complex was deformed along thrusts and sub-isoclinal folds producing steeply dipping phyllites and slates. It was uplifted by 3–5 km during the Kalahari epeirogeny between 140 and 60 Ma while eroding at ca. 100–200 m/m.y. (120–80 Ma). During the Cenozoic, the rate of uplift decreased by an order of magnitude and today is ca. 0.4–0.7 m/m.y. across steep slopes and canyons in contrast to the Himalayas where erosion rates are about hundred times faster. A recent publication about this central-eastern section of the Kango region disputes the existence of regional isoclinal folds and suggests that deposition of the oldest sedimentary successions, including carbonate rocks of the Cango Caves (limestone-marble with enigmatic microfossils) was simple, continuous and restricted to between ca. 700 and 500 Ma, decreasing earlier estimates of the stratigraphic age range by 60–80%. Similarly, recent interpretations of the complex landscapes link the northern contact between the Kango and Table Mountain rock sequences to Quaternary faults. We present a new geological database, mapped between 1:500 and 1:10,000 scales, and twelve stratigraphic sections with younging directions linked to structural and isotopic data that support repetitions along regional isoclinal folds and thrust zones of the Kango sequences during the Permo–Triassic Cape orogeny, and geomorphic data that link the origin of its landscapes to weathering and erosion during the Cretaceous–Cenozoic Kalahari epeirogeny. During its evolution, the Kango Basin directly flanked both Grenvillian and Pan-African Mountain systems. But, at an average sedimentation rate of ca. 1 mm/70 years (0.014 mm/year) and with present low erosion rates (0.005 mm/year), there is likely more time missing than preserved of the tectono-erosion across these different regions of Rodinia and Gondwana before Africa emerged. To further evaluate the geodynamic significance of these time gaps requires more field mapping linked to new transdisciplinary geosciences.

RÉSUMÉ

La région du Kango (Cango) flanque les marges nord du petit Karoo et des montagnes du Cap dans la province du Western Cape en Afrique du Sud. Elle préserve une stratigraphie con-

densée protérozoïque–paléozoïque exposée via une morphologie mésozoïque–cénozoïque avec une topographie actuelle de type alpin. Ses roches et ses paysages ont été cartographiés et documentés durant les 150 dernières années. Au cours des 25 dernières années, nous avons re-cartographié et daté une section du centre-est de cette région. Les roches litées de manière subverticale et clivées révèlent une stratigraphie de 8 à 10 km d'épaisseur couvrant plus de 700 millions d'années entre environ 1200 et 500 Ma avec plusieurs non-conformités et disconformités. À 252 Ma, au cours de l'orogénèse du Cap, ce Complexe du Kango s'est déformé le long de chevauchements et de plis isoclinaux produisant des schistes à fort pendage. Il a été soulevé de 3 à 5 km au cours de l'épirogenèse du Kalahari entre 140 et 60 Ma, tout en s'érodant à 100–200 m/m.a. (120–80 Ma). Pendant le Cénozoïque, le taux de soulèvement a diminué d'un ordre de grandeur et il est aujourd'hui d'environ 0,4 à 0,7 m/m.a. à travers des pentes abruptes et des canyons, contrairement à l'Himalaya où les taux d'érosion sont environ cent fois plus rapides. Une publication récente sur cette section du centre-est de la région du Kango conteste l'existence de plis isoclinaux régionaux et suggère que le dépôt des plus anciennes successions sédimentaires, y compris les roches carbonatées des Grottes du Congo (marbre calcaire avec des microfossiles énigmatiques) était simple, continu et limité entre environ 700 et 500 Ma, diminuant les estimations antérieures de la tranche d'âge stratigraphique de 60–80%. De même, des interprétations récentes des paysages complexes relient le contact nord entre les séquences rocheuses du Kango et de Table Mountain à des failles quaternaires. Nous présentons une nouvelle base de données géologiques, cartographiée à des échelles entre 1:500 et 1:10,000, et douze coupes stratigraphiques avec des directions de superposition liées à des données structurales et isotopiques qui concordent avec les répétitions le long des plis isoclinaux régionaux et des zones de chevauchement des séquences du Kango pendant l'orogénèse permo–triassique du Cap, et des données géomorphiques qui relient l'origine de ses paysages à l'altération et à l'érosion au cours de l'épirogenèse du Kalahari au Crétacé–Cénozoïque. Au cours de son évolution, le bassin du Kango flanquait les systèmes montagneux grenvillien et panafricain. Mais, à un taux de sédimentation moyen d'environ 1 mm/70 ans (0,014 mm/an) et avec les faibles taux d'érosion actuels (0,005 mm/an), il manque probablement plus d'enregistrements de la tectonique et érosion de ces différentes régions de Rodinia et Gondwana avant l'émergence de l'Afrique que ce qui est actuellement préservé. Pour évaluer la signification géodynamique de ces intervalles de temps manquant, il faut d'avantage de cartographie de terrain associée à de nouvelles géosciences transdisciplinaires.

Traduit par la Traductrice

INTRODUCTION

Geographically, the topography of the Kango (in Afrikaans) or Congo (in English) across the Klein Karoo and Cape Mountains of southern South Africa comprises a paleo-plateau about 1200–1000 m above sea level (asl), incised by dendritic drainage valleys up to 400 m deep that originate along the

southern flanks of the ca. 2000 m asl Swartberg Mountains (Fig. 1A), and from which tributaries, such as the Grobbelaars River, meander along the present east–west Congo Valley at ca. 600 m asl. In a few places along the Congo Valley, rivers diverge south in steep canyons that cut through this paleo-Congo plateau and in more open valleys across the lower Oudtshoorn Plateau at ca. 500 m asl, to join the larger Olifants River near Oudtshoorn at ca. 300 m asl (Figs. 1B and 2).

Lester King (1951; pers. comm. 1980) first suggested that the geomorphology of the Congo Valley, including the famous Congo Caves, represents a 'Tertiary' erosion surface with sub-surfaces (caves) excavated along old fault zones linked to Cenozoic uplift of southern Africa. More recently, Geoffrey King (pers. comm. 2005; King and Bailey 2006) suggested that the distinct different elevations and geomorphic features separating the hard quartzites of the Swartberg Mountains and the softer sedimentary rocks of the lower lying Congo sequences are linked to Tertiary normal faulting along this contact.

More recent seismic and magnetic data (Stankiewicz et al. 2007; Lindeque et al. 2007, 2011; Weckmann et al. 2012) and fission track and cosmogenic geochronology (Tinker et al. 2008; Decker et al. 2011, 2013; Scharf et al. 2013; Kounov et al. 2015) across this area have shown that the uplift and erosion of the Congo Valley and adjacent mountain systems were linked to epeirogeny with rapid erosion rates (100–200 m/m.y.) during relatively wet conditions of the Early Cretaceous to mid-Cenozoic era, and decreased more than ten-fold during drier climate conditions in the late Cenozoic, reaching very low erosion rates of less than 0.4–1.5 m/m.y. today and over the last 2 to 5 m.y. Thus, the rugged present-day topography across the Congo Valley and the Swartberg Mountains is inherited predominantly from the Cretaceous and has been only minimally re-sculptured by 200–300 m denudation during the late Cenozoic (Kounov et al. 2015). Lester King's 'Tertiary' surfaces, often covered by large quartzite pebbles and boulders are consequently late Mesozoic in age (Fig. 1C).

The famous Congo Caves formed within limestone and marble are massive sinkholes up to 2000 m long and 15–20 m high (Luttman-Johnson 1897), with a number of chambers along a subhorizontal shaft about 270 m below the surface of a well-preserved part of the paleo-Congo plateau ca. 1000 m asl. The caves are incised by a modern drainage that links to the more recent low-eroding surfaces (< 2 m/m.y.) and dendritic drainage valleys (3–6 m/m.y.; see Fig. 2b and details below; for general information and images of the caves see https://en.wikipedia.org/wiki/Congo_Caves). Stalagmites within the Congo Caves are abundant and relatively recent in age (< 200 ka; de Wit et al. unpublished).

Geologically, the Kango rocks across the Congo Valley were originally reported to be older than the Malmesbury Series (Ediacaran; Nama System) and thus linked to parts of the Namaqualand Schist (Dunn 1887), and named the 'Congo Beds' by Corstorphine (1886). Thereafter these rock sequences were mapped as 'a series of slates, grits and sheared conglomerates, among which bands of dolomite of very varying thickness occur', with 'quartz–feldspar-grit or porphyroids, and diabase in the form of numerous dykes, often much altered by

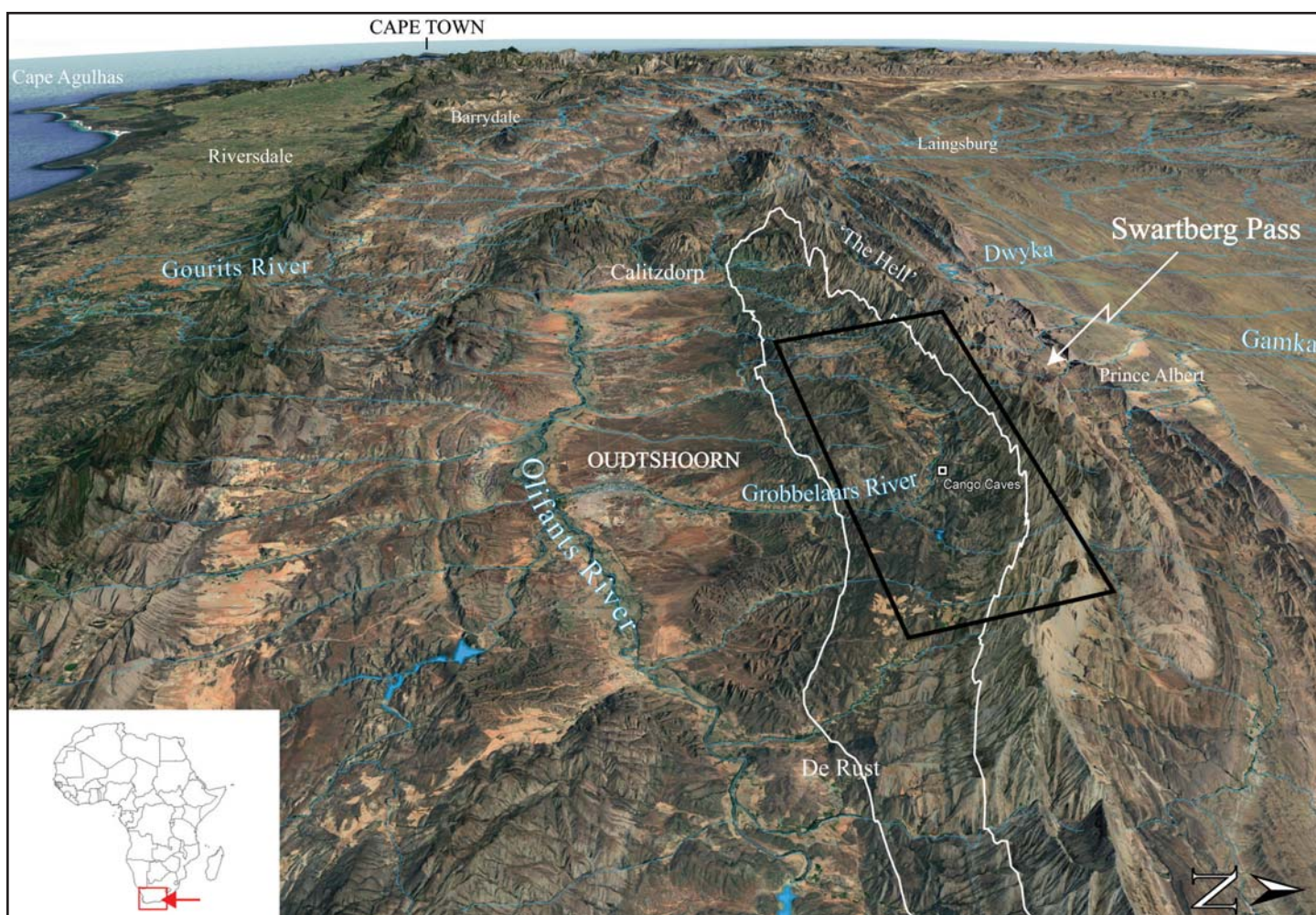


Figure 1A. Topographic image of the Proterozoic Kango Inlier (white outline) in southern South Africa, highlighting the elongate mountain range of the Swartberg (quartzite) from which small dendritic river systems flow to the north and south; the latter at relatively low catchment-averaged denudation rates of ca. 3–6 m/m.y. Two deep meandering rivers that cut across Swartberg quartzite terminate along the northern flanks of the Swartberg Mountains. A third major meandering river system (the Gamka–Dwyka rivers) cuts across the entire mountain range and joins the Olifants River near Calitzdorp. In the centre of the Swartberg, to the southwest of Prince Albert, a sequence of younger Paleozoic shales has eroded to create the subparallel Gamkas-kloof (-valley), locally known as ‘The Hell’. These regional geomorphologic features illustrate a complex erosion history, linked to variable uplift and climate changes from the Cretaceous to the present (see text), and which is well preserved across the present reported area of the Kango Complex (black rectangle).

shearing’, and recorded as the ‘Cango Series’ (Corstorphine and Rogers 1897; Rogers and Schwartz 1900; McIntyre 1932).

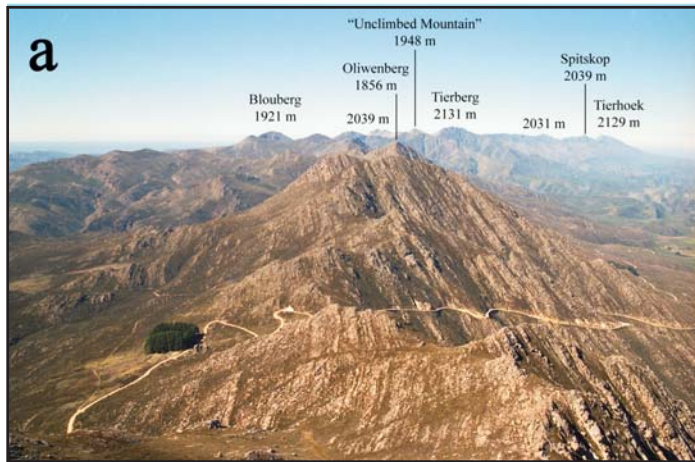
Tectono-stratigraphically, the Kango sequences comprise folded and cleaved meta-sedimentary rocks interpreted to underlie unconformably the near-vertical conglomerates and quartzites of the Table Mountain Group (TMG) across the narrow Swartberg Range. A similar south-dipping tectonic sequence of TMG (with conglomerates) flanks the southern margin of the Kango rocks. The latter, in turn, is tectonically overlain by Upper Mesozoic ‘Enon’ red sandstones and conglomerates of the Uitenhage Group, exposed at the contact with the TMG quartzites by a listric fault that today is still seismically active (Fig. 2c; Söhne and Hälbig 1983; Gresse et al. 1993; Goedhart and Booth 2016; Linol and de Wit 2016).

The first detailed geological map (1:50,000) with sections across the central Cango region was produced by Stocken (1954). This is an exceptional map in that, for the first time, the lower sequences were recognised as a series of structurally

repeated, subvertical limestone and shale units along east–west regional isoclinal folds and refolds, separated from younger sequences by large-scale thrusts. In particular, a major isoclinal antiform, with an axial strike length of ca. 7 km, was shown to duplicate the lowermost stratigraphy of the Cango Group, then named the Hilda Series. However, no dips of the fold limbs or fold axis, nor their plunges are shown on Stocken’s map.

Subsequently, the structural complexity of these tectonic features was mapped in greater detail across the entire Cango region (Le Roux 1977, 1983; Le Roux and Gresse 1983), as recorded in a special publication of South Africa’s National Geodynamics Programme (Söhne and Hälbig 1983; Nicolayson 1983). This field work established a more detailed stratigraphy of seven formations (Fig. 3), in which, for example, the Hilda Series was renamed the Matjies River Formation, as part of a Goegamma Subgroup that, together with an overlying Kansa Subgroup, were referred to as the Kango Group and

Swartberg Pass Panorama



Cango Valley Panorama



Figure 1B. Landscape photographs flanking the Cango Valley. (a) Northeast-focused view across the Swartberg Mountains near the road crossing the Swartberg Pass at 1583 m asl along the road towards Prince Albert and the Karoo Basin (to the north; a_N) and the Kango Basin (to the south; a_S). Beds of Table Mountain Group (TMG) rocks (quartzites of the Lower Paleozoic Cape Supergroup) are overturned, dipping steeply south and younging north. (b) Views across the Cango Valley taken 15 km to the south of the Swartberg Pass, highlighting remnants of a wide open, relatively flat erosion surface near 1000 m asl across the Kango rocks and presently cut by the Grobbelaars River meandering across another flat surface, with farmland, at ca. 750 m asl (b_E , view to east and b_W , view to west).



Figure 1C. West-facing views, taken from slightly different angles, across the 1200 m asl paleo-Cango Valley (ca. 200 m above De Hoek Camping Resort – pale green grass) linked to the Swartberg Mountains (top right) along gentle to open paleoslopes. These remnant flat surfaces of Late Mesozoic age are incised by steep dendritic drainage valleys linked to wider sections like near the resort. There is no field evidence of faults that might have initiated these younger geomorphologic valleys. The changes in valley systems are linked to precipitation and tectonic changes during the Kalahari epeirogeny from around 140 to 60 Ma (see text).

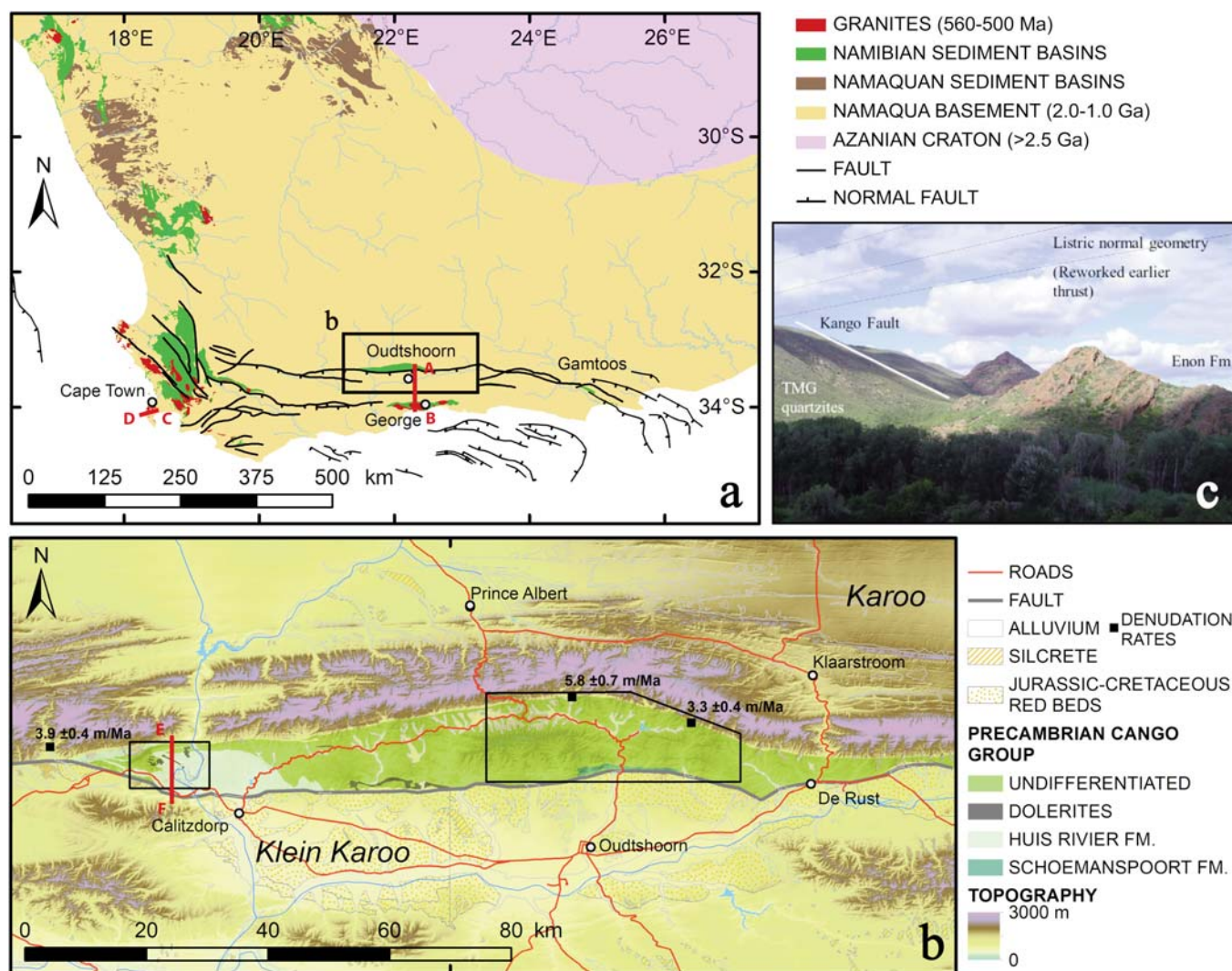


Figure 2. (a) Simplified geological map of the Cango/Kango region across Paleo- to Neoproterozoic crust of the Namaqua Natal Belt bordering the southern margin of the Archean Azanian craton; cross-sections A–B and C–D are shown in Figure 37. (b) The Proterozoic to Paleozoic Cango Group forms the southern flank of the Swartberg Range of the Cape Mountains, bounded to the south by a major Mesozoic–Cenozoic fault system (c). Black polygons delineate the study areas; cross-section E–F is shown in Figure 30. The low denudation rates across a number of variable river systems are from Scharf et al. (2013).



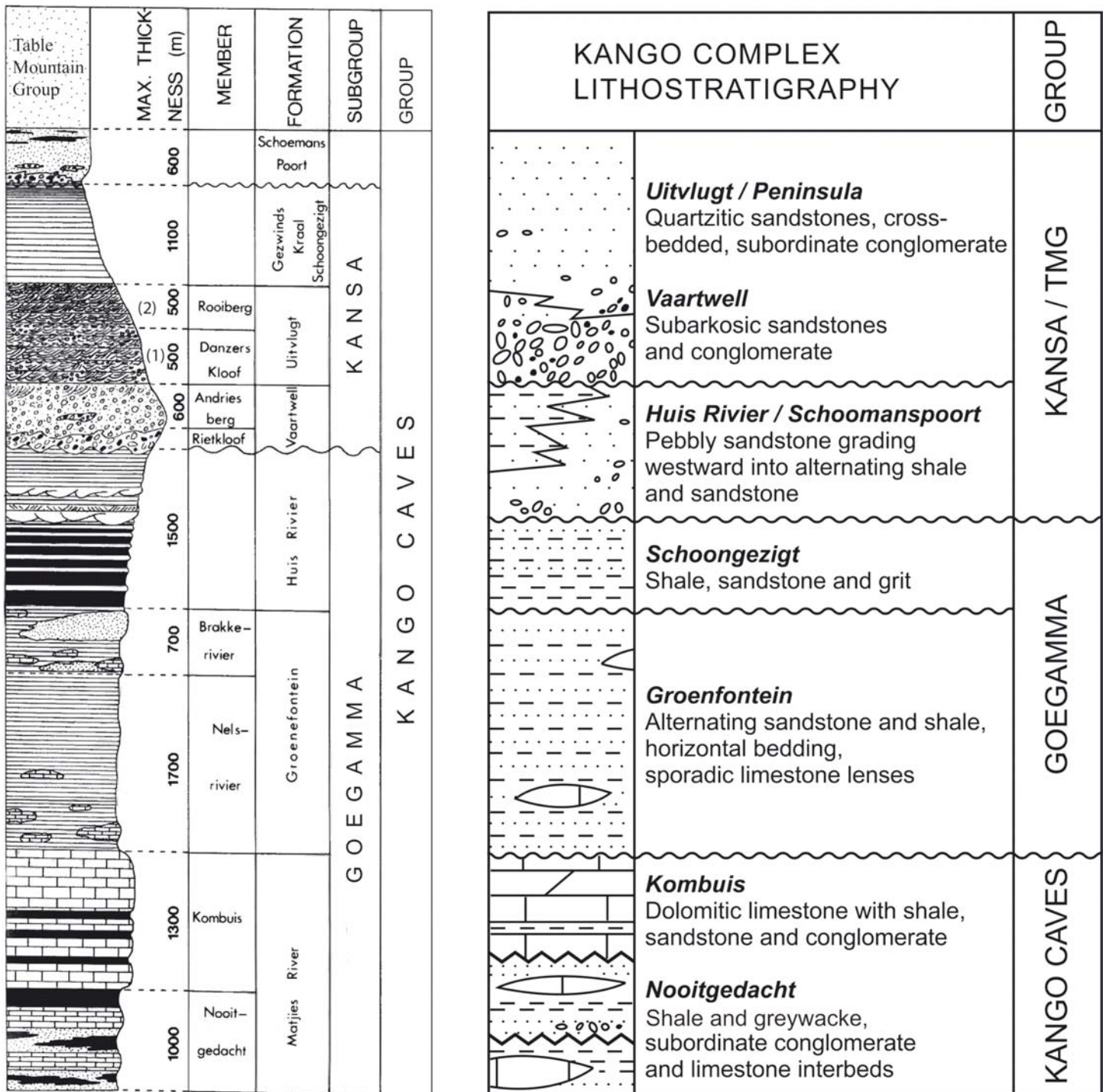


Figure 3. Stratigraphy of the Kango Complex. (Left) Modified from Le Roux and Gresse (1983), with subgroup (Goegamma and Kansa) renamed, and with members Danz-erkloof (1) and Rooiberg (2) as inverted by Naidoo et al. (2013). (Right) Simplified lithostratigraphy redivided here into three groups as described in detail across twelve field sections in this study. In this new framework the Schoongezigt Formation is part of the Goegamma Group; the Schoemanspoort Formation links to the base of the Kansa Group; and the Uitvlugt Formation of the upper Kansa Group is of equivalent age to the lower TMG (Table Mountain Group). Major unconformities: wavy lines = previous work; angular lines = this work.

separated by a major unconformity (Le Roux and Gresse 1983; Gresse et al. 1993). Both the subgroups were shown to be unconformably overlain at different localities and stratigraphic levels by the TMG.

This previous work also yielded a map with eight detailed sections that cover the exposed stratigraphy of the Kango inlier west of 23°E (from east to west, ca. 150 km long and 14 km wide across the central Cango region; Le Roux et al. 1983).

The sections highlight the regional south-dipping folds and fault systems, but on which the major fold closure recognised by Stocken is poorly displayed. This fold, and many sub-folds along its limbs, was later remapped and measured in detail as a steep ($> 70^\circ$) west-plunging anticline by numerous groups of students at UCT and NMU.

The Kango stratigraphy has since been subdivided further through more local mapping and petrology, often linked to new metamorphic analyses, geochemistry, and dating techniques that confirmed a Neoproterozoic–Early Paleozoic age range of the upper sequences using detrital zircons (e.g. Le Roux and Smit 1995; Barnett et al. 1997; Fölling 2000; Frimmel et al. 2001; Frimmel 2009; Van Staden 2011; Naidoo et al. 2013).

Sedimentary structures preserved in many field sections across the Kango sequences are commonly overprinted and replaced by macroscopic regional schistosity/cleavage, linked to microscopic minerals such as sericite, chlorite and carbonate flakes of low-grade metamorphism (Stocken 1954; Le Roux 1983; Hällich 1983a, b; Barnett et al. 1997; Frimmel et al. 2001), at about 350°C (Hällich 1983a, b), consistent with isochore data from oxygen isotopes in quartz–calcite veins that yield trapping temperatures up to 410°C (Egle et al. 1995, 1998; Egle 1996).

All Kango rocks reveal moderate paleo-weathering based on CIA (Chemical Index of Alteration) with arenite showing slightly higher CIA than carbonate rocks. Overall, the alteration values are relatively homogeneous with slightly increased alteration stratigraphically upward across the siliciclastic sequences of the Kansa Subgroup (Naidoo 2008; Naidoo et al. 2013).

U/Pb Geochronology

Detrital Zircon Dates from the Kango Sequences

Stocken (1954) was the first to describe in detail zircons in both sedimentary rocks and intrusions across the Congo region. Typically sandstone (arenite) is rich in zircon (30–60% of all non-opaque heavy minerals), apatite (up to 50%), and rutile (minor), and there is a marked similarity in heavy minerals from different formations that range from well-rounded to angular, all commonly coated with iron oxide (e.g. Stocken 1954; Barnett 1995; Naidoo 2008).

U–Pb analysis of detrital zircons to test an age difference between the lowermost sandstone of the Kansa Subgroup (Rietkloof Unit of the Vaartwell Formation; Fig. 3, left) and subvertical shales of the underlying Groenfontein Formation of the Goegamma Subgroup yielded a maximum Late Cambrian age in the former, with a $^{206}\text{Pb}/^{238}\text{U}$ date of ca. 518 ± 9 Ma found directly above the unconformity separating these two sequences (Barnett et al. 1997). The samples also revealed a subset of well-rounded zircon grains with Mesoproterozoic dates around 1100 Ma.

By contrast, near euhedral zircon grains from a coarse feldspathic grit near the bottom of the Kango Caves Group (Nooitgedacht Member; Fig. 3, left) only yielded $^{206}\text{Pb}/^{238}\text{U}$ dates between 1200 and 1050 Ma; and a number of detrital zircons from carbonate conglomerate (diamictite) of the Matjies

River Formation along the road to the Congo Caves yielded dates between 1360 and 1060 Ma (Barnett 1995; Barnett et al. 1997; de Wit et al. unpublished).

U–Pb detrital zircon dates from a much larger number of sampled sequences across the Congo region confirm the Cambro-Ordovician age of the Kansa Subgroup, with a predominance of Early to Middle Cambrian zircons, and with older Mesoproterozoic grains ranging from ca. 1034 ± 2 to 1377 ± 14 Ma and 1800–1900 Ma. In addition, a number of Neoproterozoic zircons in the Kansa and the lower TMG sequences were recorded with dates ranging from 620 to 911 Ma (Naidoo et al. 2013) and abundant Mesoproterozoic and Neoproterozoic ages were found in the Huis Rivier Formation of the Goegamma Group to the west of the present study area (ca. 1029 ± 7 to 1083 ± 40 Ma, and 571 to 911 Ma; Naidoo et al. 2013). A lack of GPS locations for these samples does not allow further detailed analysis and stratigraphic comparison.

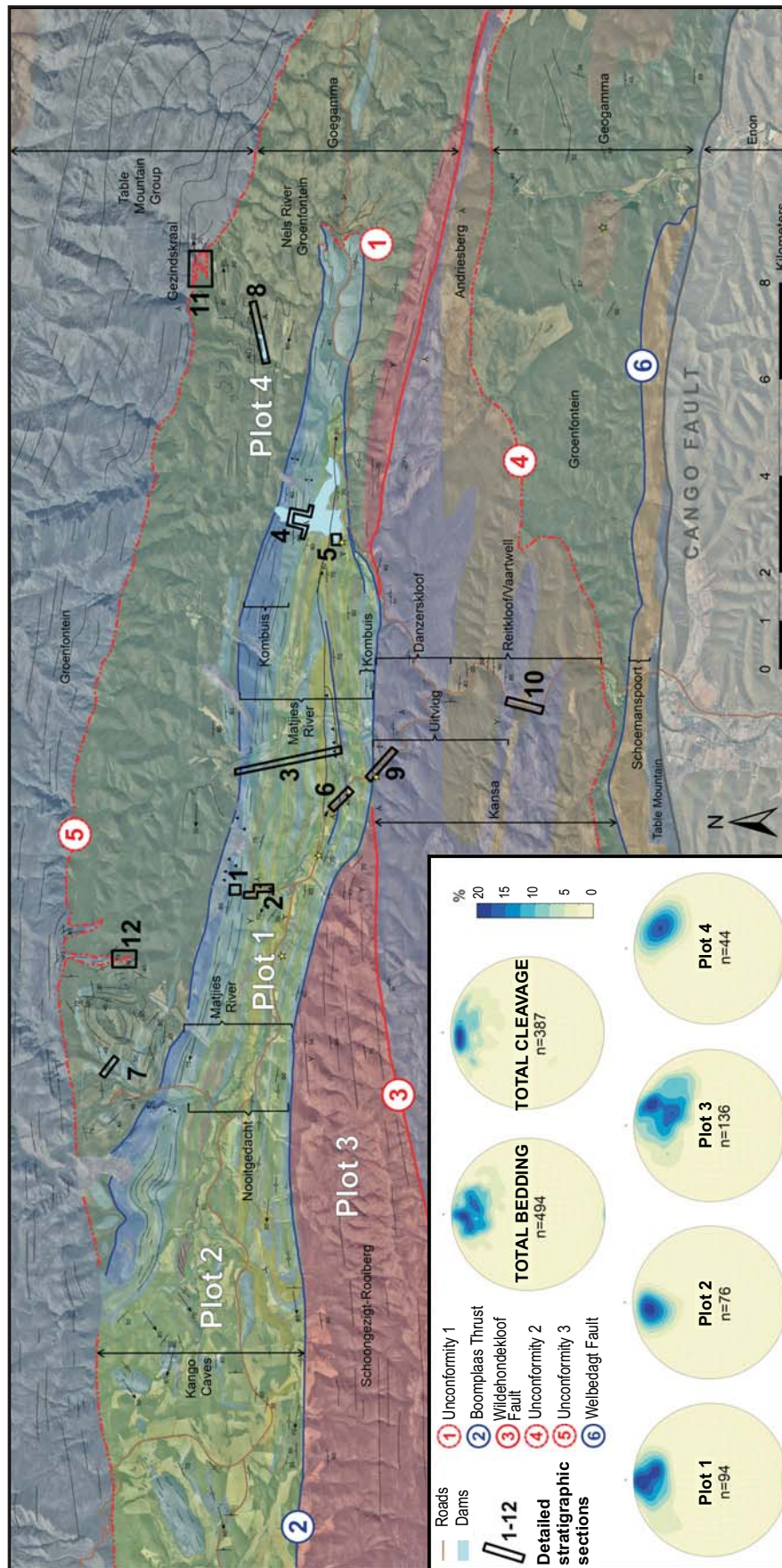
Igneous Zircon Dates from Felsic and Mafic Dykes

In two places across the lowermost Kango Caves Group, felsic dykes cut the Nooitgedacht sequences. These dykes have not been described or reported on before. The best exposed dykes are found along the southern section of the Raubenheimer Dam (see Map 1 and Section 5), where they cut across thick bedded sandstone. Zircons from two of these felsic dykes, both of which are cleaved and partially weathered, yield a concordant U–Pb date of ca. 1072 ± 5 Ma. At a second locality, along the road section 700 m before the turn-off to the Congo Caves (see Map 1 and Section 6), at least five thin subvertical felsic dykes cut across thinly bedded, folded (vertical axis) sandstone and carbonate rocks. Zircons from three of these dykes yielded a concordant U–Pb date of ca. 1078 ± 5 Ma. Thus, the lower sequences of the Kango Complex are Mesoproterozoic in age.

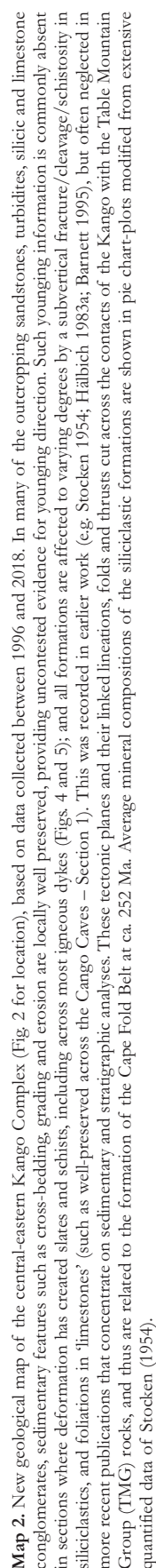
A number of mafic dykes across the Kansa rocks in the eastern section of the Kango Complex (see Fig. 2b) yielded younger ages: the first, a dolerite-gabbro with a U–Pb zircon date of ca. 512 ± 10 Ma (Haas 1998); and the second, a schistose dyke with a U–Pb zircon date of ca. 460 ± 5 Ma (de Wit et al. unpublished). Thus, these mafic dykes are Early Paleozoic in age, although the date of the second dyke may have been partially reset during the formation of its schistosity at 252 Ma (Booth 2011; Blewett and Phillips 2016; and see below).

While the precise ages of the stratigraphic sequences between the upper and lower Kango Complex remain unknown, our mapping confirms a relatively thin, but complex tectono-stratigraphy over a period of more than 700 million years. In contrast, more recent work questions the fold and fault systems, and recognises only unconformities mapped previously. This results in a simplified stratigraphy, confining the age of the lower Congo sequences between ca. 700 and 500 Ma (Nel et al. 2018). Previous Pb–Pb double spike isochron data from the Kombuis carbonate units yielded an age of ca. 553 ± 30 Ma, and C and Sr isotope signatures similar to those found in sequences separating a pre-Ediacaran from a Vendian (Ediacaran) age (Fölling 2000; Frimmel et al. 2001; Frimmel 2009). However, the clastic nature of the carbonate rocks





Map 1. General map highlighting names of stratigraphic sections as in previous publications, and the new stratigraphic sections (Sections 1 to 12) and described in the text. Stereoplots 1 to 4 summarize local bedding and cleavage of four areas, shown with white labels.



(detailed below and in Section 2) questions the primary nature of these different data.

These major disagreements justify stratigraphic testing which we present here based on long-term field mapping across the central-eastern Congo region and geochemical analyses in RSA, Australia, USA, Canada, and Europe over the last 22 years. We provide a detailed geological map (Map 2) and twelve sections, two of which are linked to new U–Pb zircon dates on felsic igneous intrusions, and we re-examine the stratigraphy and tectonic history of this unique inlier within the Cape Mountains.

REVISED GEOLOGICAL MAP

Mapping was conducted using various sets of aerial photographs, enlarged at scales between 1:500 and 1:10,000 over 22 years (1997–2019) and consolidated at a scale of 1:25,000 (GIS available online: www.aeon.org.za/cangomap). The results, including measured planar fabric, dip and fold axis, are summarized here on condensed maps with linked stereoplots (Maps 1 and 2). This work reveals four major stratigraphic sequences with strikingly different ages, separated by three regional unconformities and two major tectono-sedimentary boundaries, one of which links to a major molasse-type sequence (simplified on Fig. 3; and see below).

Tectonic structures complicate reconstruction of precise stratigraphy, locally and regionally (Fig. 4). The two oldest sequences (formerly the Matjies River and Groenfontein formations) are isoclinally folded with major fold axes plunging steeply east and west, which makes the measurement of total thicknesses difficult, something that was clearly recognised by Stocken (1954). These are tectonically overlain along the Boomplaas Thrust to the south by a sequence of red beds (the Schoongezigt and Gezwinds Kraal formations, in total about 1000 m thick), and in turn unconformably overlain across the Wildehondekloof Fault by more than 1500 m thick conglomerates and greywackes, referred to as the Vaartwell and Uitvlugt formations (Le Roux and Gresse 1983). To the north, this ‘Kango Complex’ underlies north-younging quartzites of the Peninsula Formation, the lowermost unit of the TMG, but which in places is overturned, dipping 40–70° to the south (Fig. 1B). A sliver of hard quartzites, also from the TMG, bounds the southern edge of this complex along the Congo Fault (Map 1).

Before reporting on twelve detailed new sections, we first summarize below the wide range of ductile–brittle deformational features and structures, especially cleavage and schistosity, that occur throughout most of the study area, but which are generally not reported and/or interpreted as sedimentary structures.

Variable Regional Deformation Structures – Shear Zones, Schists and Faults

Published geology of the Congo region generally underplays the existence of major deformational features such as folds, shear zones and faults. Here we highlight some of these structures and elaborate on them in the following field sections and on Map 2.

Deformational features in thick limestone and marble are particularly difficult to quantify because of limited preservation of original bedding and low strain recrystallization. Occasional carbonate (dolomite) beds of dark colour reveal internal isoclinal folding (Fig. 4A). Deformed limestone and carbonate conglomerate are well preserved throughout the lower sequences (Fig. 4B). In many places, these foliated carbonate rocks locally reveal mylonitic textures, including in and adjacent to the Congo Caves (Fig. 4C).

General Regional Stratigraphy

We have changed the stratigraphic successions of the Congo region by recasting the present two subgroups and one group into three groups: the Kansa, Goegamma and Kango Cave Groups, based on the identification of major unconformities and several tectonic boundaries (Fig. 3, right; and detailed below). In addition, our new mapping is consistent with recent detrital zircon data (e.g. Naidoo et al. 2013), which confirm that the upper Kansa Group overlaps in age with the Table Mountain Group (TMG).

The two oldest sequences of the Kansa Group are separated by two major unconformities, commonly tectonically overprinted, the younger sequence of which, with sandstones and conglomerates of the Andriesberg Formation (formerly a member), has detrital zircons dated at 518 Ma (Barnett et al. 1997), and is thus Cambrian (or younger) in age. This age is similar to that of detrital zircons in the lowermost formation (Peninsula Formation) of the TMG along Table Mountain in Cape Town, dated at 520 Ma in the same laboratory (Armstrong et al. 1996; Scheepers and Armstrong 2002), and from the same lowermost TMG quartzite in the Swartberg Mountains flanking the Kango rocks (518 to 504 Ma; Naidoo et al. 2013). Stratigraphically younger zircon grains (ca. 471 Ma) occur in conglomerate and sandstone sequences of the Gezinskraal Formation, the lowermost section of which is unconformably below the TMG, and directly above the Groenfontein Formation (Map 2).

Elsewhere the Huis Rivier and Schoemanspoort formations have detrital zircons dated between 620 and 485 Ma (Naidoo et al. 2013). Thus, the entire Kansa Group is younger than ca. 520 Ma (Cambrian) and possibly ca. 470 Ma (Silurian), predominantly derived from Late Neoproterozoic sources dated between 650 and 620 Ma (Barnett et al. 1997; Naidoo et al. 2013).

The overlying Vaartwell and Uitvlugt sequences comprise thick conglomerates (with various granite clasts) interbedded with and fining upwards into cross-bedded sandstones and siltstones (Section 9). The large-scale ripple cross-laminations with mud drapes and common rip-up clasts suggest a shallow marine, wave-dominated paleo-environment (e.g. Walker and James 1992). This is similar to, albeit deeper than, the coastal marine setting generally proposed for sedimentation of the more mature quartzites of the Peninsula Formation (Shone and Booth 2005).

In general, pre-Goegamma arenites have microscopic textures of quartz-rich tectonites modified by fracturing and recrystallization of a crenulated chlorite–sericite matrix (Fig.





Figure 4A. (a, b) Examples in the Congo Caves limestone and marble of near-isoclinal folds, and (c) folded and boudinaged dolomite layers (pale grey), with white calcite extension fractures in clastic limestone (dark grey). For location a–b see Section 1; location c, Raubenheimer Dam, see Section 4.



Figure 4B. (a) Deformed carbonate boulders (blue-grey) in chlorite–muscovite schist (brown and green) of the Nooitgedacht Formation along the southern limb of the Congo Caves ‘limestone’. (b) Isoclinal folded and foliated limestone and marble (blue-grey). (c) Massive subvertical pelitic schist (pale brown and green) cut by quartz veins – these are extensive throughout the studied region, but especially well preserved along thick sections (> 100 m) near the Congo Caves (Section 2).

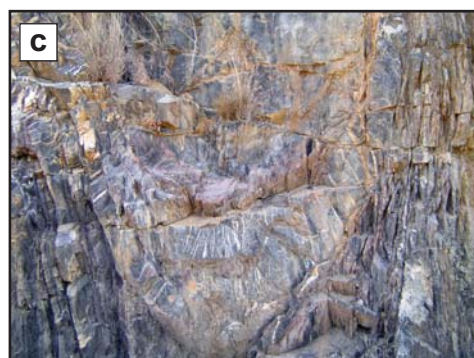


Figure 4C. Typical example of subvertical shear zones separating two different folds styles, both with subvertical axes, in two tectonically separated stratigraphic sequences of the Kango Caves Group. (a, b) Left, grey-blue marble with white calcite veins; and right, shallow dipping pale brown sandstone with minor shale, separated by schist and mylonite (highlighted sections in red) of vertical shear in the lower sequences. (c) Close-up of the subvertical, sub-isoclinal fold of marble in (b) (black outline), with variably angled white calcite veins from axial planar to nearly orthogonal across bedding planes.

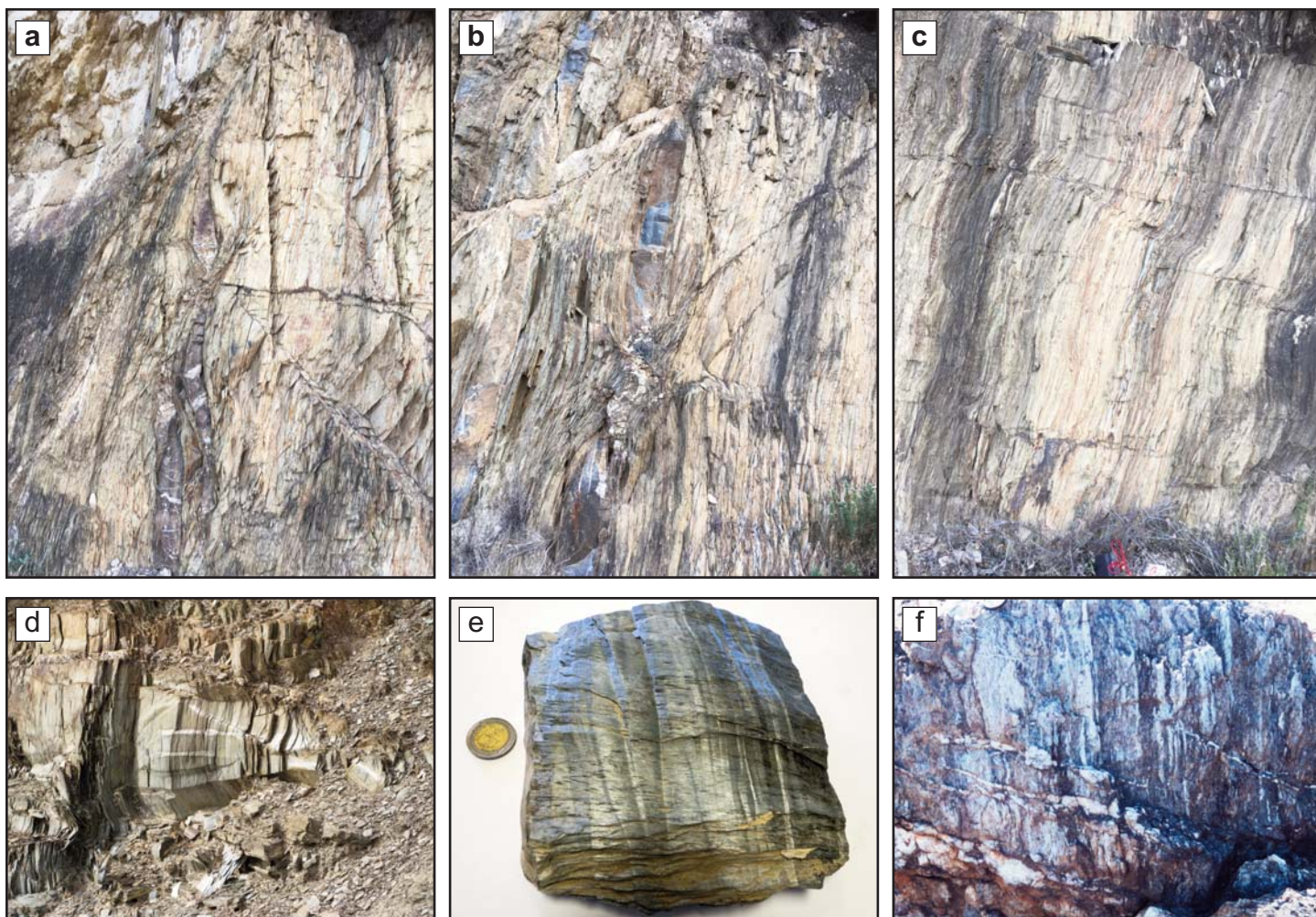


Figure 4D. Typical sections across subvertical mica slate and schist (pale brown) zones (a–c), with folded and boudinaged marble sheets (blue grey with white calcite veins), locally with (d) subhorizontal kinks and vertical tectonic lineations of mica (e) crenulation cleavage (black), and (f) quartz (white). For location a–c see Section 6.

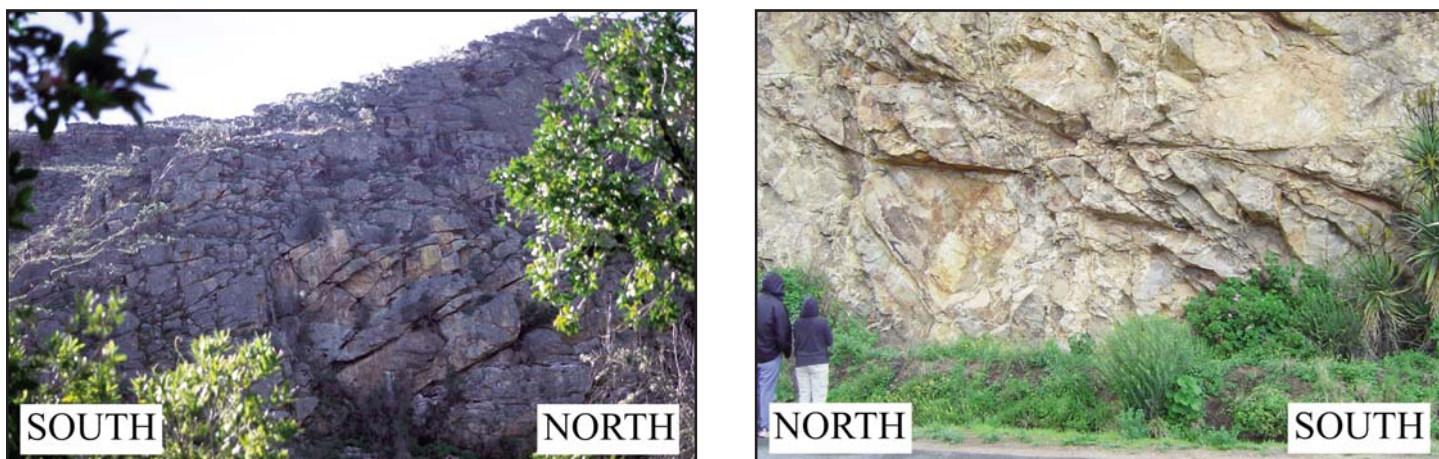


Figure 4E. TMG quartzites flanking the north and south boundaries of the Kango Complex. (Left) North boundary of complex, steep and shallow north-trending thrusts across the contact between the Kango and TMG rocks (Section 11). (Right) South boundary of complex brecciated and brittle thrusts in TMG quartzite at Schoemanspoort near Section 10.

4D). Thick sequences of K-feldspar-dominated arenite are common, often with large, angular and poorly sorted orthoclase and microcline. Albite-oligoclase plagioclase is less common and always small in grain size. Minor orthopyroxene also has a wide distribution. Zircon, apatite, rutile, epidote and tourmaline make up 95–100 % of the non-opaque heavy minerals, of which zircon is the most abundant. Selected zircon grains from major coarse, poorly sorted feldspar–quartz sandstones in the lowermost sections of the Nooitgedacht Formation, in places directly flanking the Congo Caves to the south (pale brown in Map 1), have been dated between ca. 1377 and 1090 Ma (Barnett et al. 1997; Naidoo et al. 2013).

Between these coarse arenite (and local slate) units of the Nooitgedacht and the Kombuis formations, are the thick sequences of massive Congo Caves carbonate layers and lenses (commonly referred to as limestone – e.g. Stocken 1954; Naidoo et al. 2013; Nel et al. 2018). These are dark grey, with numerous folded and boudinaged calcite–quartz veins (Section 1). The clastic nature of the limestone is evident from the ubiquitous presence of detrital limestone fragments and clasts, calcite grains, ooids and variable concentrations of quartz and feldspar grains in the more arenaceous carbonate rocks. In many places, carbonate sandstones and conglomerates, grading to large boulders, represent complex deposition processes (Sections 2–4 and 7).

The oldest preserved Congo strata comprise variable conglomerates and sandstones that contain poorly sorted pebbles of granitoid gneiss and pegmatite interlayered with unsorted carbonate and quartzite clasts that range from centimetres to several metres in size, commonly with local unconformities and disconformities (Section 3; see also Nel et al. 2018). The characteristic mineralogy and clast lithologies attest to limited transport from the eroded sources and conditions favourable to the preservation of the feldspar. This suggests erosion of a granitic terrane adjacent to a sea or lake with limited reworking, and/or cold, possibly subglacial conditions.

Thus, while the uppermost conglomerate beds across the Kango Complex (Kansa Group) are predominantly well-sorted quartzite with well-rounded granite boulders interbedded with cross-bedded sandstone, the top and bottom of the Congo carbonate sequences are characterized by poorly sorted carbonate conglomerate commonly with limestone boulders in excess of 1 m in diameter.

Mafic dykes are common across the entire Kango Complex, and in most cases are strongly cleaved or schistose (Fig. 5a). The geochemistry of the basaltic andesite has been reported elsewhere (e.g. Barnett et al. 1997; Van Staden et al. 2006; Van Staden 2011); in the western Congo region, they have been dated at ca. 512 ± 10 Ma (Haas 1998). Felsic dykes (Fig. 5b) have only been encountered in the lowermost sections of the Kango Caves Group (the Nooitgedacht Formation). The REE of the felsic dykes are similar to those of the mafic dykes (Fig. 5c), but their dates, presented here for the first time, are very much older (Section 7).

Tectonic contacts between and within the Kango sequences are common (Fig. 4E and Map 2), and it remains unclear how the different sequences are linked stratigraphical-

ly. Below, we first provide an example of a general deformed section across the Congo Caves, followed by detailed analyses across eleven other sections, from the oldest to youngest, which, when linked to published data and the structural analyses reveal that a new stratigraphy is required for the studied region. This we attempt at the end. The locations of all geo-sections described below are shown on Map 1.

Stratigraphy of Twelve Cross Sections Based on Lithology and Structural Data

Section 1. Foliated Marbles of the Congo Caves

Highly deformed carbonate rocks are exposed within the Congo Caves (Fig. 6), here referred to as Congo marbles, and along their contacts with 80–200 m thick pelitic schists.

Good exposures of deformed marble flank the entrance of the caves, along strike below the edge of the car park and along the partly exposed roofs within the caves (Fig. 7). Massive 'limestone' marble with calcite veins and boudins is tectonically foliated. Similar tectonic zones are common in parts of the Kango Caves Group across the entire studied region, but are often difficult to quantify, since the carbonate rocks are usually recrystallized, weathered, and poorly exposed. It is therefore not possible to measure accurately the tectonized sections of the Kango Caves Group (see also Stocken 1954); however deformed carbonate layers and conglomerates (Figs. 7 and 8) confirm extensive deformation throughout the Congo carbonate rocks, including those flanking, and interbedded in the Groenfontein Formation (Section 9).

Section 2. Conglomerates and Phyllites Along the Road to the Congo Caves

To the south, the Congo limestone is flanked by boulder conglomerates and phyllites of the Nooitgedacht Formation, more than 500 m across (Fig. 8). The contact is a fault zone with 80 m thick green fine-grained phyllite to schist locally with sandstone interbeds with some preserved crossbedding that indicates younging directions to the south. This road section cuts across thick bedded conglomerate and coarse sandstone, in total 40 m thick, younging north, in the opposite direction, highlighting a tectonic boundary. The conglomerate is clast-supported, with angular to sub-rounded pebbles of granite pegmatite, granite gneiss, with coarse blue quartz and white feldspar matrix, and rounded, poorly sorted boulders of carbonate between 0.1 and 3 m in diameter (Fig. 9A). These lithologies reveal the relative proximity of two distinct sources: first from coarse-grained granite and pegmatite intrusions, and second from carbonate platforms from which exotic limestone blocks were derived. The limestone boulders resemble 'megabreccia' beds of the Cow Head Group, western Newfoundland, deposited as talus sediments (e.g. Hiscott and James 1985; James and Stevens 1986). Such a process of rapid, catastrophic deposition indicates a high topography such as along continental slopes and submarine escarpments (Coniglio and Dix 1992; Ager 1992).

Well-exposed outcrops along the road reveal multiple unconformities and anticlinal structures plunging southwest



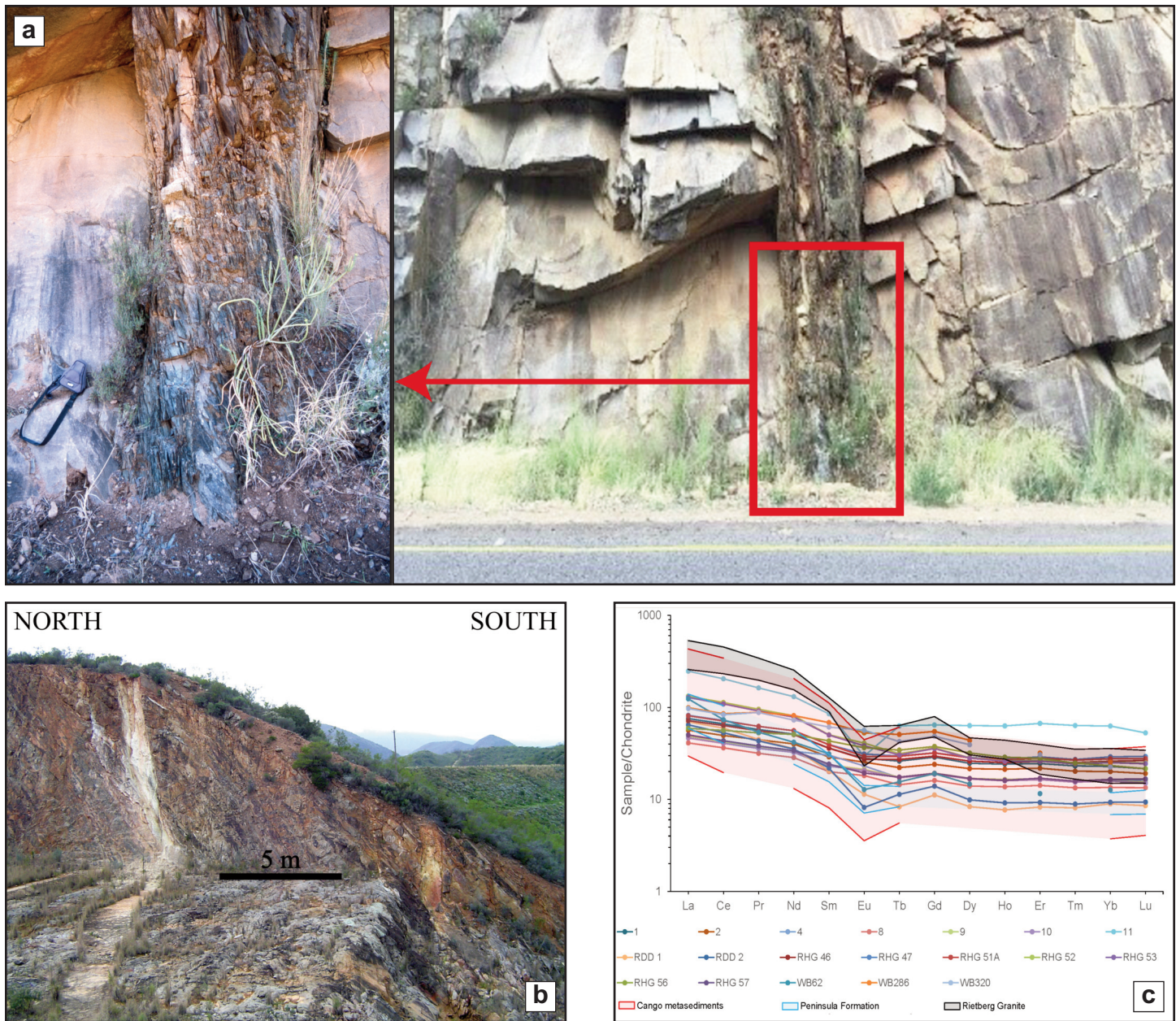


Figure 5. (a) Typical green schistose dolerite dyke (vertical) with extended quartz veins intruding poorly deformed quartz-dominated sandstone (subhorizontally bedded) of the Vaartwell Formation along the Schoemanspoort road (Section 10). Igneous zircon grains from this and similar dykes date between 550 and 450 Ma (see text); the geochemistry of the dykes is typical basaltic-andesitic. (b) White, fine-grained schistose and weathered silicic dykes intruding south-dipping sandstone of the lowest exposed sequence (Nooitgedacht Formation) of the Kango Caves Group. U–Pb-dated zircon grains are older than 1000 Ma; the geochemistry of these dykes is andesitic. (c) Normalized rare earth elements for rock samples of the Kango Complex compared to data from Macey et al. (2018; the Rietberg Granite dated at 1033–1086 Ma) and Naidoo et al. (2013; the Congo and Peninsula sedimentary rocks).

(N275). Boulder conglomerate (40 m thick) is clast- to matrix-supported, with angular to sub-rounded pebbles and large blocks of carbonate, feldspar, pegmatite and blue quartz (Figs. 8 and 9B). It is overlain by carbonate schist, phyllite and again boulder conglomerate but with larger blocks (1–3 m), although it is not clear if these beds are repeated.

The good outcrops exposed farther down along the road show several unconformities (Fig. 10). Although grading and cross-lamination of sandstone interbeds within the phyllite indicates younging directions to the south, it is not clear if the

succession is repeated more than once. Southward the boulder conglomerate becomes thicker (80 m thick) with larger limestone boulders up to 3 m in diameter. Large quartz veins cut across this sequence (Fig. 8).

Section 3. Massive Sandstones, Clastic–Carbonate Rocks and Boulder Beds Between Groenfontein and Grootkraal

A 2 km long, north–south cross-section is described flanking the valley between Groenfontein and Grootkraal (Figs. 11 and

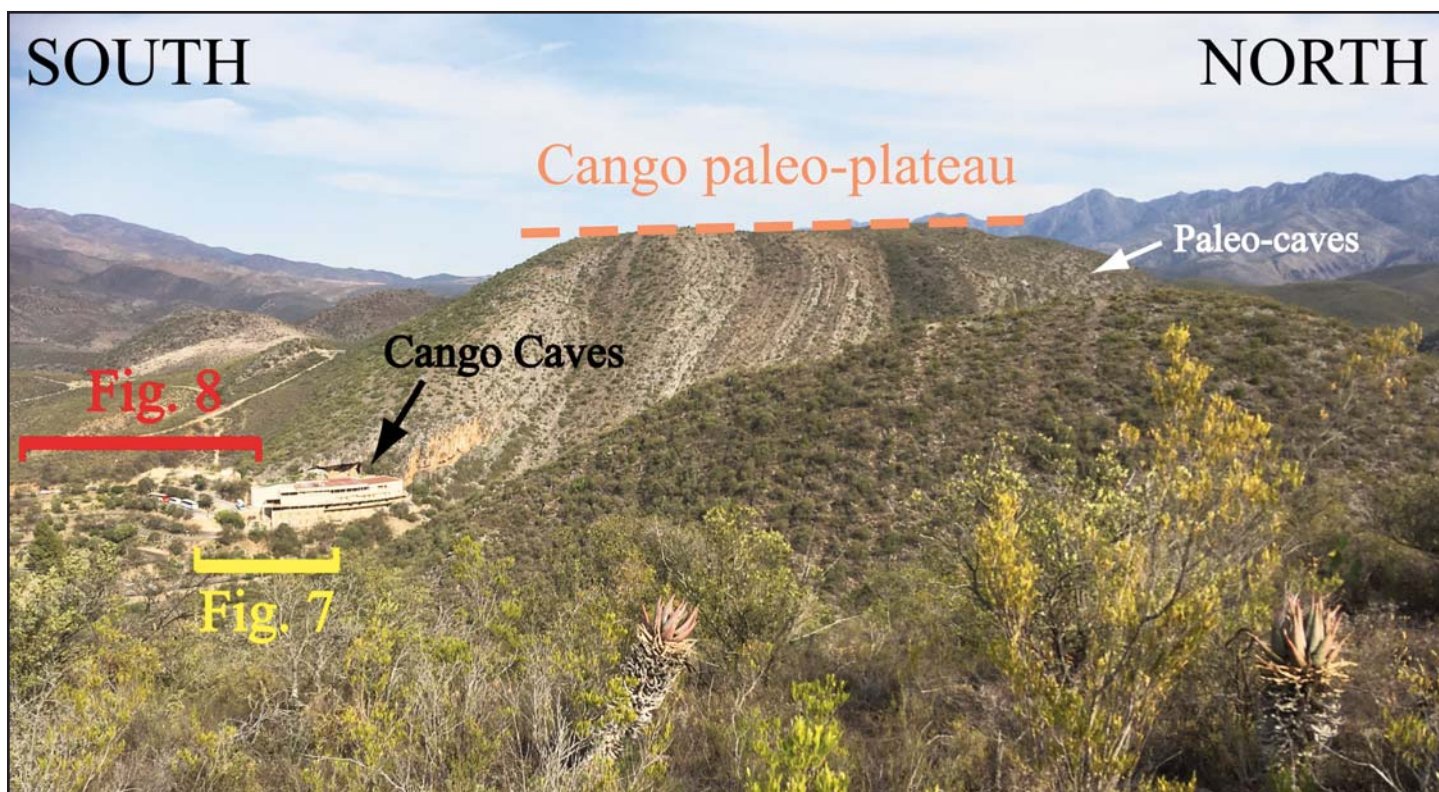


Figure 6. Westward view across the Congo Valley with generally poorly exposed limestone in the foreground, highlighting the well-exposed steep south-dipping ($70\text{--}80^\circ$) inter-layered sequences of Congo 'limestones' (pale grey carbonate rocks) and shales (green, and generally covered by vegetation) of the Kombuis Formation (Section 1, Map 1). The famous Congo Caves occur close to the contact between the southernmost carbonate layers and pelitic schist; here the carbonate rocks are highly deformed (see Figs. 7 and 8). Paleocaves and sinkholes are also preserved along the northern boundary of the carbonate with overlying turbidites of the Groenfontein Formation; for all cave locations see Map 2.

12). Linked to north-younging Congo massive limestones and carbonate conglomerates of the Kombuis Formation along its tectonic contact with the Groenfontein Formation, is a large syncline–anticline fold pair of coarse feldspathic sandstones, thick sequences of phyllite, and clastic-carbonate rocks with boulder beds (the Nooitgedacht Formation; Fig. 3).

These rocks are deformed along tight, axially subvertical folds (Figs. 13 and 14A), and it is not clear how much stratigraphic thickness is missing along the tectonic zone that separates the phyllites from the feldspathic sandstones, and particularly across the tectonically thinned carbonate layers flanking the southern part of the cross-section (Fig. 12). A change in bedding directions across a subvertical cleavage confirms large ($0.5\text{--}1$ km) anticlinal and synclinal structures.

To the south, more abundant green phyllites and massive carbonates terminate with 10 cm to 2 m-thick clastic-carbonate pebble beds that alternate with fine and coarse-grained limestone, with sharp laminations, cross-stratifications and relatively abundant soft-sediment deformation structures, characteristic of turbidites. All reveal younging directions to the south (Fig. 14B). Near Grootkraal Farm, this succession is 125 m thick, bounded by a subvertical slate shear zone (Fig. 13). Bedding becomes progressively thicker upward to the south and passes up into carbonate conglomerate beds (with sub-angular to well-rounded boulders), $0.5\text{--}5$ m thick, separated by sandstone layers (Fig. 14C). Truncations at the bases of some

of the beds (Fig. 14D) suggest that the general southward coarsening and thickening trend of this prograding sequence results from gravity flows. These are interpreted as oligomictic debrites (breccia flows) derived from slope failure, with the large clasts supported by the bulk density of the flow (e.g. Coniglio and Dix 1992).

The outcrop of these carbonate conglomerate sequences has been interpreted previously as a north-younging inverted paleo-valley (Nel et al. 2018; see their figure 10). The different sedimentary structures described here are not consistent with this interpretation (Fig. 14B–D). This suggests similar depositional conditions, albeit more distal to the boulder conglomerates described along the road flanking the Congo Caves (compare to Fig. 8).

Section 4. Phyllites and clastic-carbonate rocks of Koos Raubenheimer Dam

Farther east, along the banks of Koos Raubenheimer Dam (Fig. 15), massive sequences of clastic-carbonate rocks and siltstones to mudstones of the Matjiesrivier Formation are well exposed especially during low rainfall years. The beds young and dip between 50 and 80° north.

Along the western section (Fig. 16A), subvertical conglomerate and coarse sandstone ($115/80^\circ\text{N}$, overturned; 170 m thick) are sharply overlain by more than 100 m thick clastic limestones. The contact between the two sequences is folded



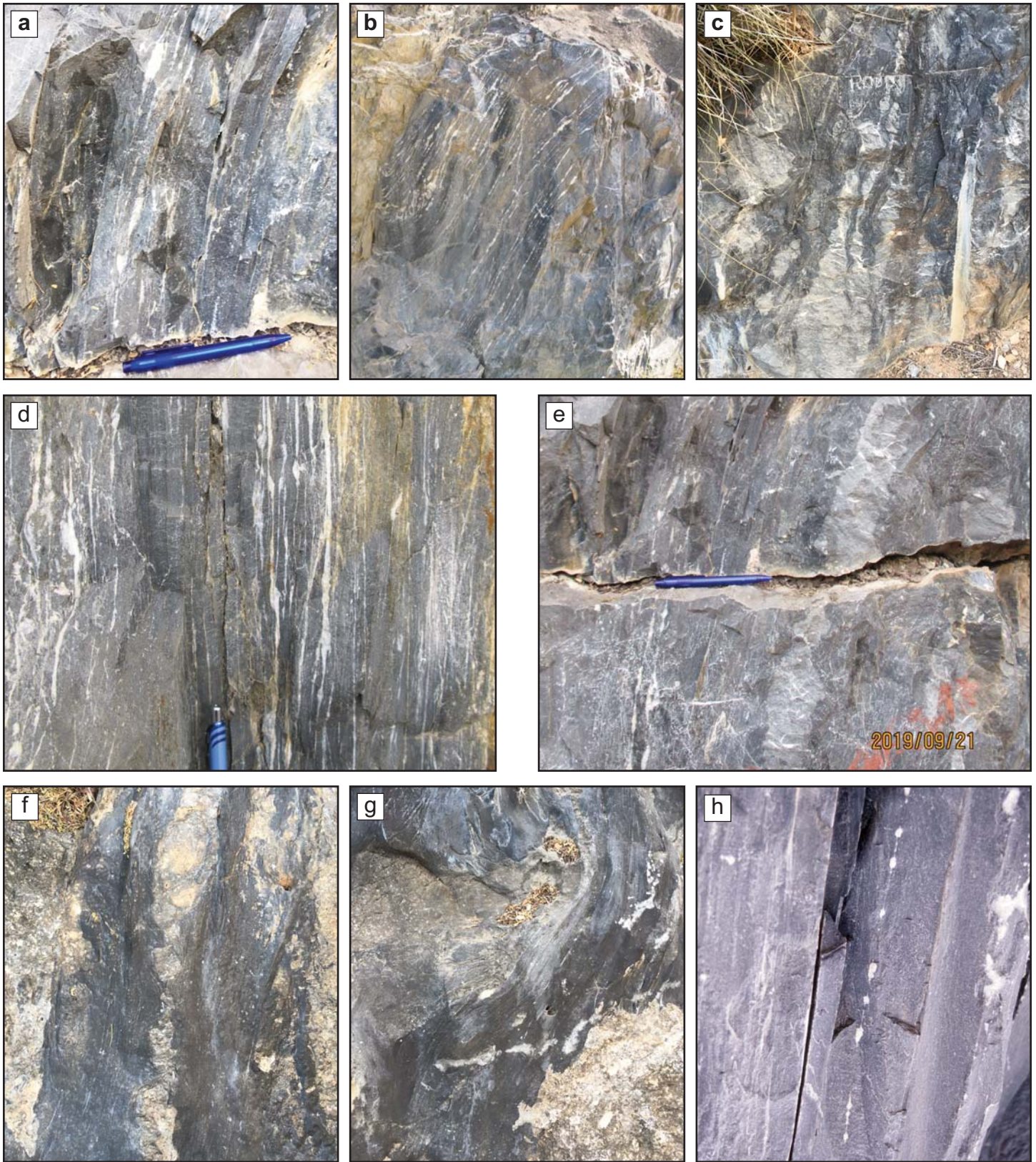
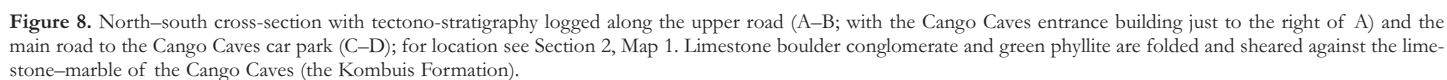


Figure 7. Foliated Congo Caves marbles with quartz–calcite veins and boudins of distinct carbonate members. Many sections like these occur throughout the Congo limestone units, separated by less deformed sequences. The deformed carbonate rocks are difficult to recognise in the Congo sections, but much of the limestone in the caves is part of these intensely deformed sections, and it remains uncertain how to stratigraphically separate the deformed and undeformed limestone/marble sequences. Top photos are from the car park below the entrance to the Congo Caves (Fig. 6); middle photos are from along the road section (Fig. 8); and bottom photos are from along the western Rauberheimer Dam (Section 4).



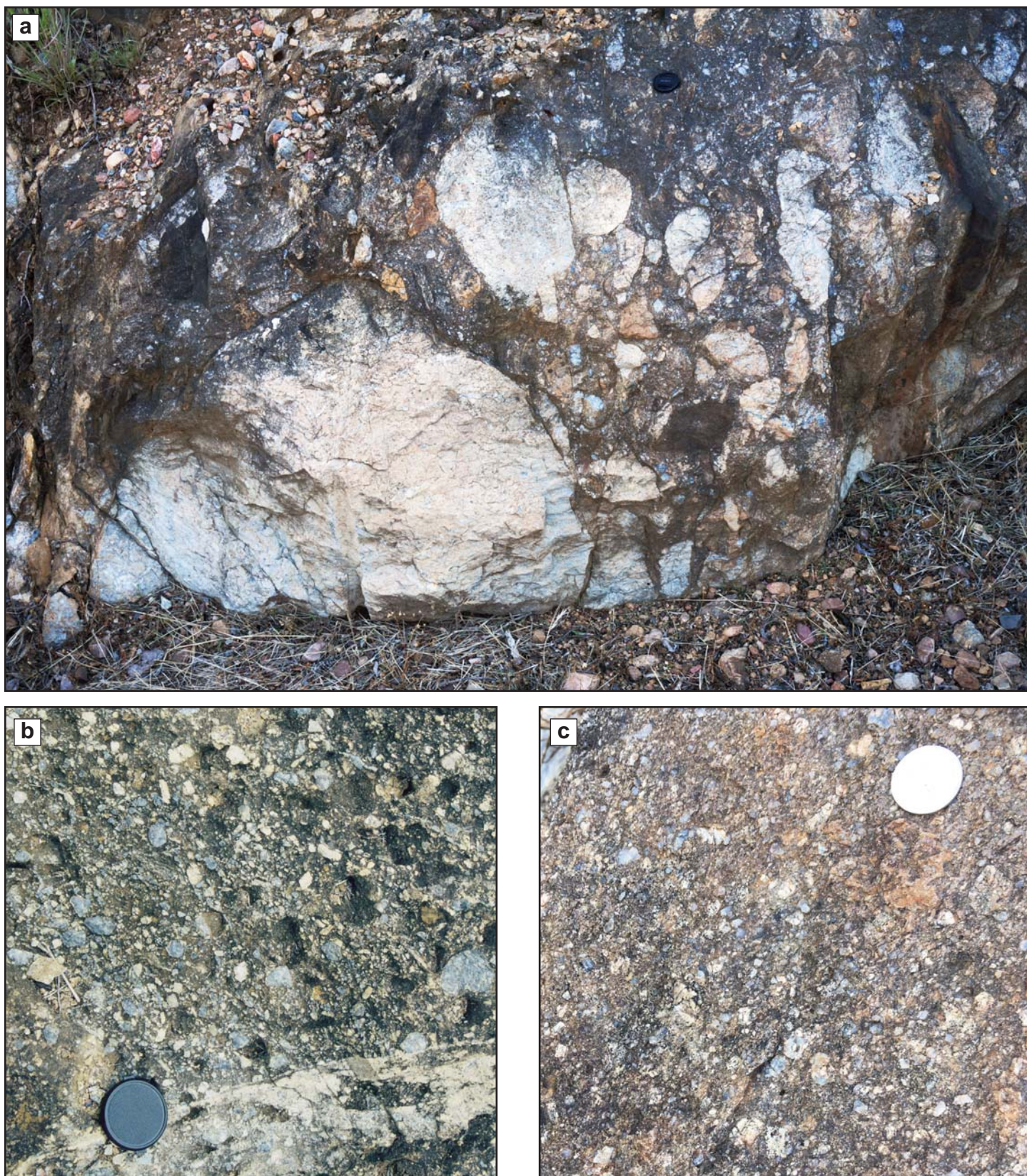


Figure 9A. (a) Graded bed of carbonate pebbles to boulders with angular to well-rounded clast- and matrix-supported pebbles of pegmatite and gneiss in feldspar-quartz matrix (Fig. 8 for location). (b–c) Typical coarse, poorly to well-sorted sandstone to grit with single white crystal K–Na plagioclase feldspars and blue quartz in the Nooitgedacht Formation. U–Pb geochronology of detrital zircons from the sandstone yielded Mesoproterozoic $^{206}\text{Pb}/^{238}\text{U}$ dates between 1200 and 1050 Ma (Barnett et al. 1997).

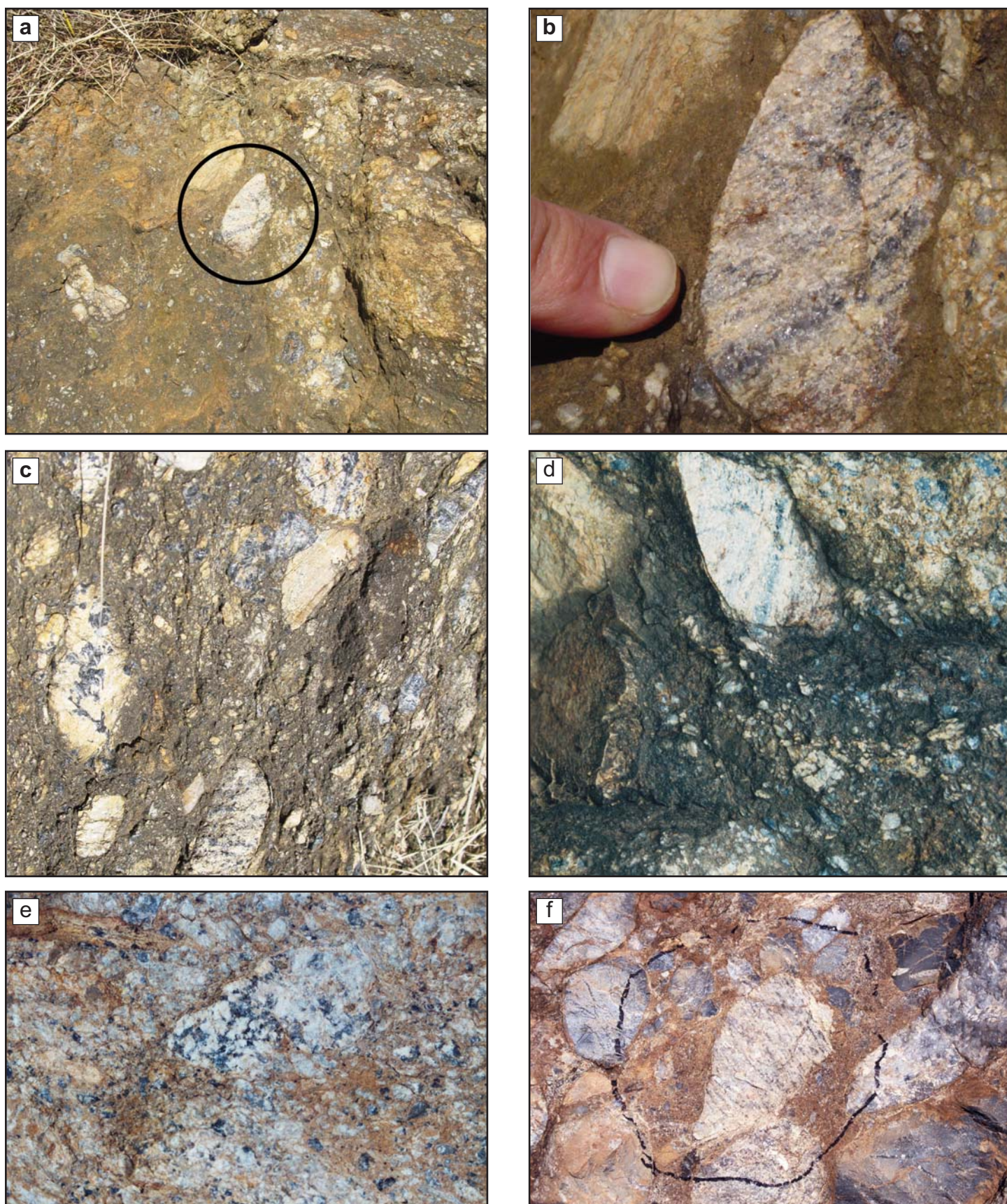


Figure 9B. Angular to well-rounded and matrix-supported small pebbles (3–7 cm long) of pegmatite and granite gneiss in feldspar–quartz matrix (Fig. 8 for location).



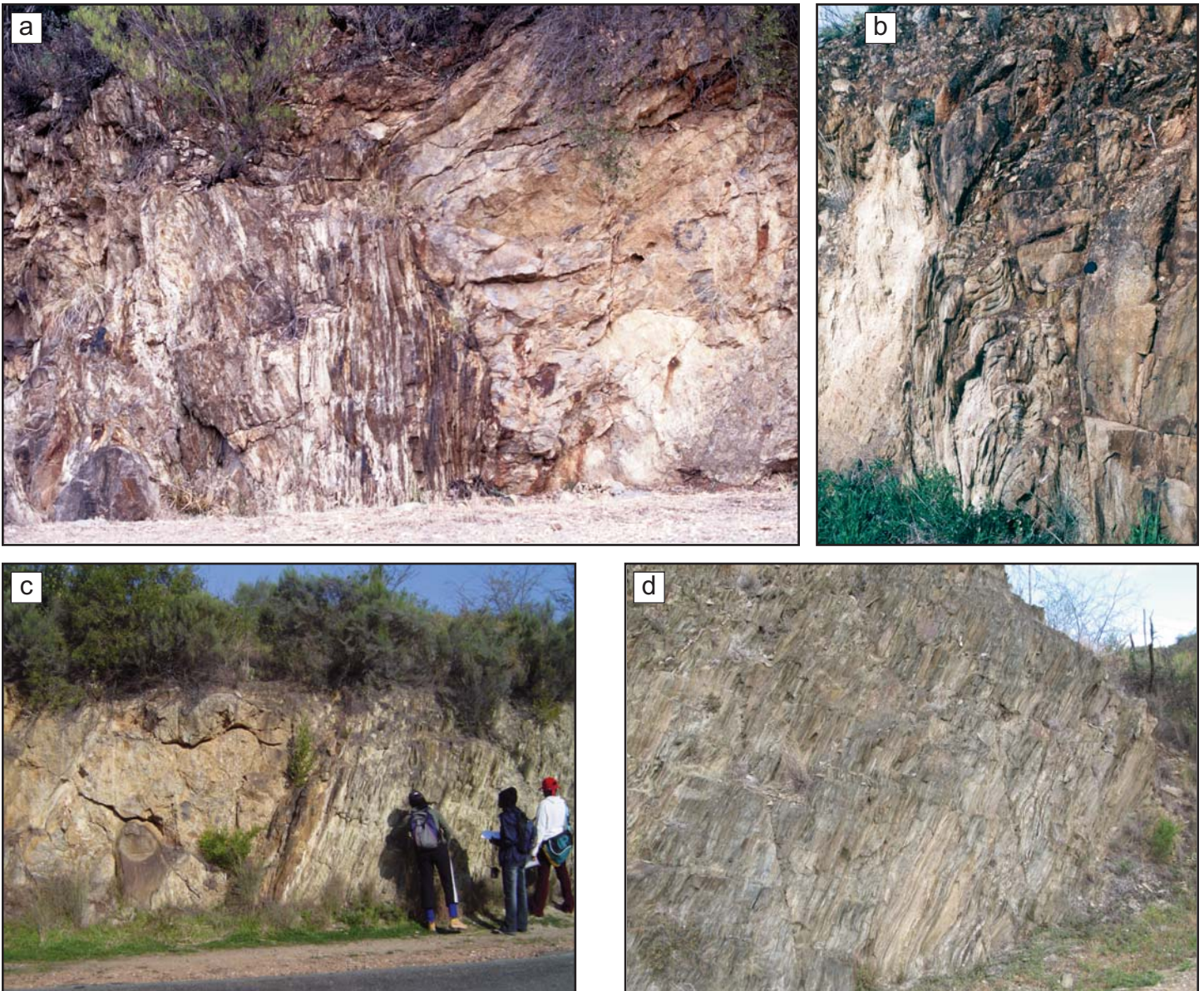


Figure 10. (a, bottom road, and b, top road) Unconformable contacts between thin bedded shale (left) and thick conglomerate-sandstone (right). (c) Tectonic contact between conglomerate-sandstone and phyllite, with (d) close-up of phyllite behind students. For locations a–c, see Figure 8.

and precipitated carbonate about 3 m thick. The lower conglomerate is composed of clast-supported small pebbles of feldspar and black quartz, grading into sandstone and shale, which suggests a younging direction to the north. Overlying sandstone comprises pebbly to very coarse-grained beds with shale interbeds that have a cleavage of direction N275.

The clastic-carbonate rocks are thinly to thickly bedded, between 0.3 and 3 m, with matrix-supported clasts showing normal and reverse grading and passing gradually into fine sandstone and shale to the north (Fig. 16A). The clasts are mostly small sub-angular limestone pebbles and granules of quartz, and occasionally limestone boulders. This characteristic diamictite facies indicates sediment gravity flow.

Along the eastern section the sequences are also near vertical (Fig. 16B). To the south, more than 55 m of dark grey

sandstone is flanked by more deformed clastic-carbonate rocks and shales, in total 420 m thick. The lower part of this succession comprises 70 m of bedded limestone with matrix-supported clasts covered by 130 m of shale with intercalations of coarse sandstone and limestone. Shales show folding and a cleavage direction of N120. The upper part has alternating thin and thick beds of massive limestone with clasts and granules, characteristic of gravity flow and suspension deposits.

Correlations of the Kombuis carbonates across Sections 1, 2 and 3 illustrate a facies changes across ca. 10 km, with more distal slope deposits to the east-southeast (Fig. 17). These are characteristic carbonate slopes, which include different environments from shallow platform margins to the deep ocean basins, with a relatively steep continental slope (Coniglio and Dix 1992). Sediment transport by suspension settling, gravity

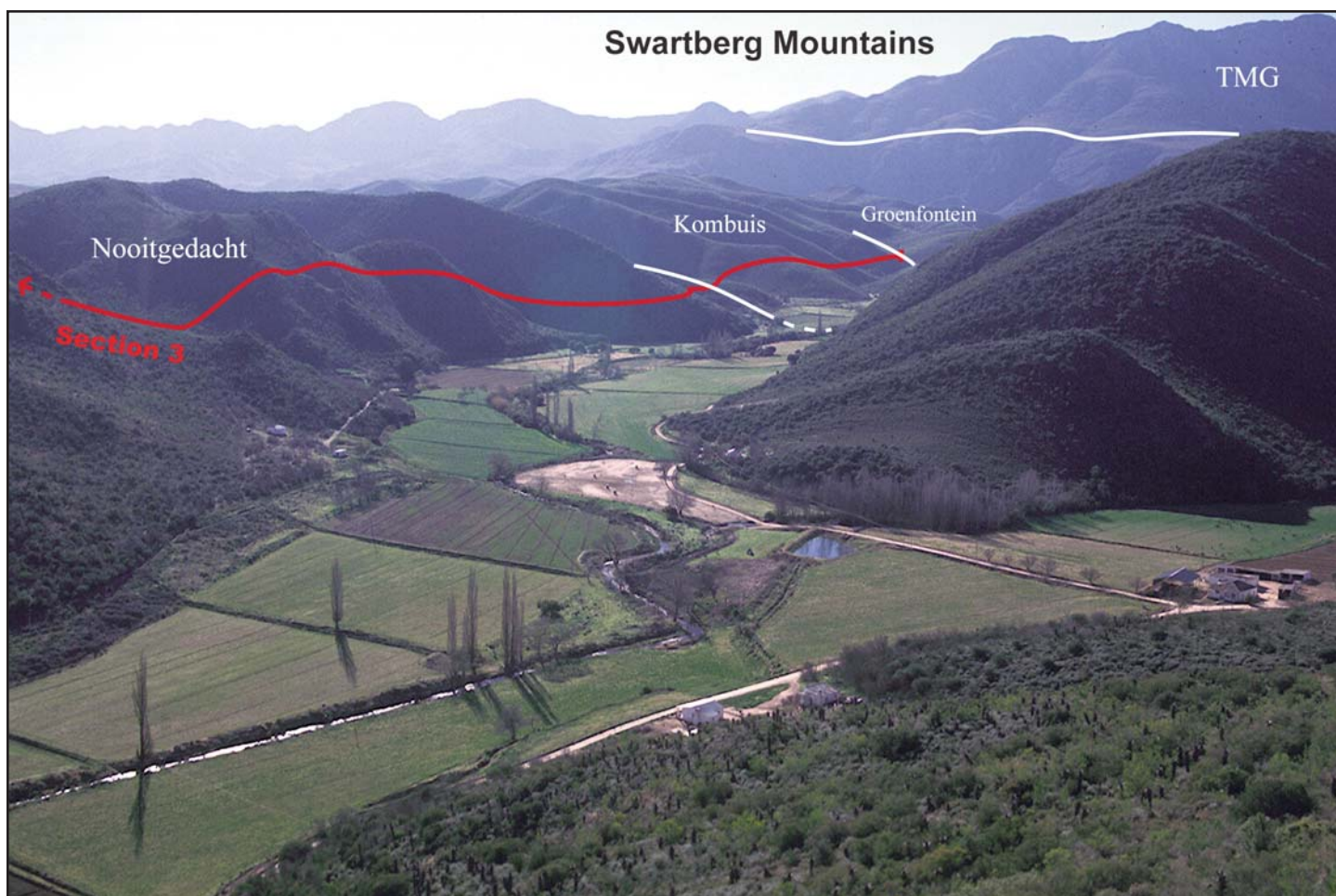


Figure 11. View north towards the Swartberg Mountains along the Tier Berg River showing mapped contacts (white lines) between the Nooitgedacht, Kombuis, Groenfontein and Peninsula formations. Stratigraphic section 3 is described in Figure 12 (Map 1 for location).

(resedimented) flow and submarine sliding often result in interbedded suspension deposits, shale and limestone, turbidites, debrites and contourites. Examples of such preserved stratigraphic records with carbonate boulder beds have been described in detail across the Cow Head Group in the Long Range Peninsula of Newfoundland (e.g. Hiscott and James 1985; James and Stevens 1986).

Section 5. Thrust Fault and Felsic Dykes Along Raubenheimer Dam Wall

Along the cut-off wall of the Raubenheimer Dam, south-dipping carbonate rocks and phyllites of the lower Nooitgedacht Formation are tectonically overlain by grey to orange, thickly bedded coarse quartzitic sandstone (grit) intruded by fine-grained felsic dykes (Fig. 18). The footwall comprises foliated carbonate rocks with extensional veins and interbedded very fine sandstone and shale. Locally preserved ripple cross-laminations show a younging direction to the south. The tectonic contact is filled with ca. 10–20 cm of schist with folded and duplicated calcite veins that reveal a north-trending thrust zone subparallel to the bedding (Fig. 19).

The new dates of two felsic dykes (Fig. 20) that cut the sandstone (and Cango limestones; see Section 6 below) of the

lower Nooitgedacht Formation are similar in age to the ca. 1070 Ma Noritoid Suite in the Nababeep district, the Kopperberg Suite and the Little Namaqualand Suite of the Khoisanland (Bushmanland) subprovince, and in general the Spektakel Suite (ca. 1100 Ma) and high-grade Namaqualand basement (e.g. Joubert 1986; see also Clifford et al. 1975, 1981; Waters 1990; Eglinton 2006). These ages confirm for the first time a much older age for the lower sequences of the Kango Complex.

Section 6. Schists, Thrusts and Felsic Dykes Along the Main Road Near Grootkraal

Well-exposed subvertical sections (Fig. 21; separated by poor exposures) of phyllite (schist) and psammite with highly deformed limestone lenses (A – ca. 250 m; and separated to the south by 500 m from schist of Section 9), are separated by about 100 m from (B) 50 m of foliated limestone thrustured across phyllite and psammite. Farther inland, the poorly exposed carbonate rocks reveal in places deformed but well-preserved carbonate conglomerates (Fig. 4B) that confirm their link to the Kango Caves Group, and together with abundant silicic schists likely the Nooitgedacht Formation (Fig. 3). Between outcrops B and C (Fig. 21), the carbonate rocks are



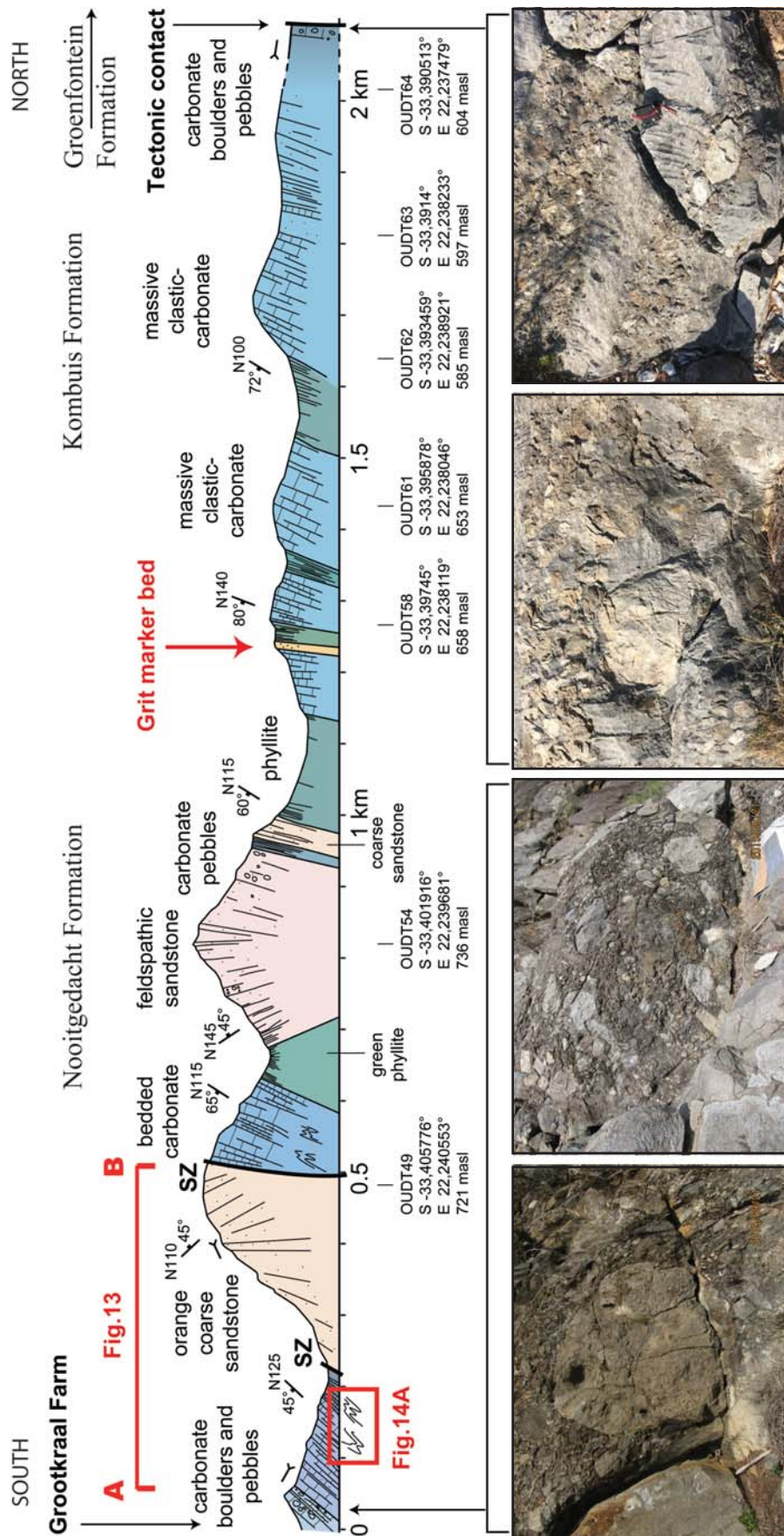


Figure 12. North-south cross section more than 2 km long between Grootkraal (south) and Groenfontein (north), showing the repetitions and contacts between limestones and shales of the Kombuis Formation and conglomerates and sandstones of the Nooitgedacht Formation (Section 3, Map 1). Highlighted in the photographs are similar limestone-conglomerate layers likely of the same upper Kombuis Formation. The massive clastic-carbonate sequences are tectonically overlain by sandstones and shales of the Groenfontein Formation that, in turn, flanks the TMG of the Swartberg Mountains to the north (fig. 11). Section A-B (with carbonate boulder beds) is detailed in Figures 13 and 14.

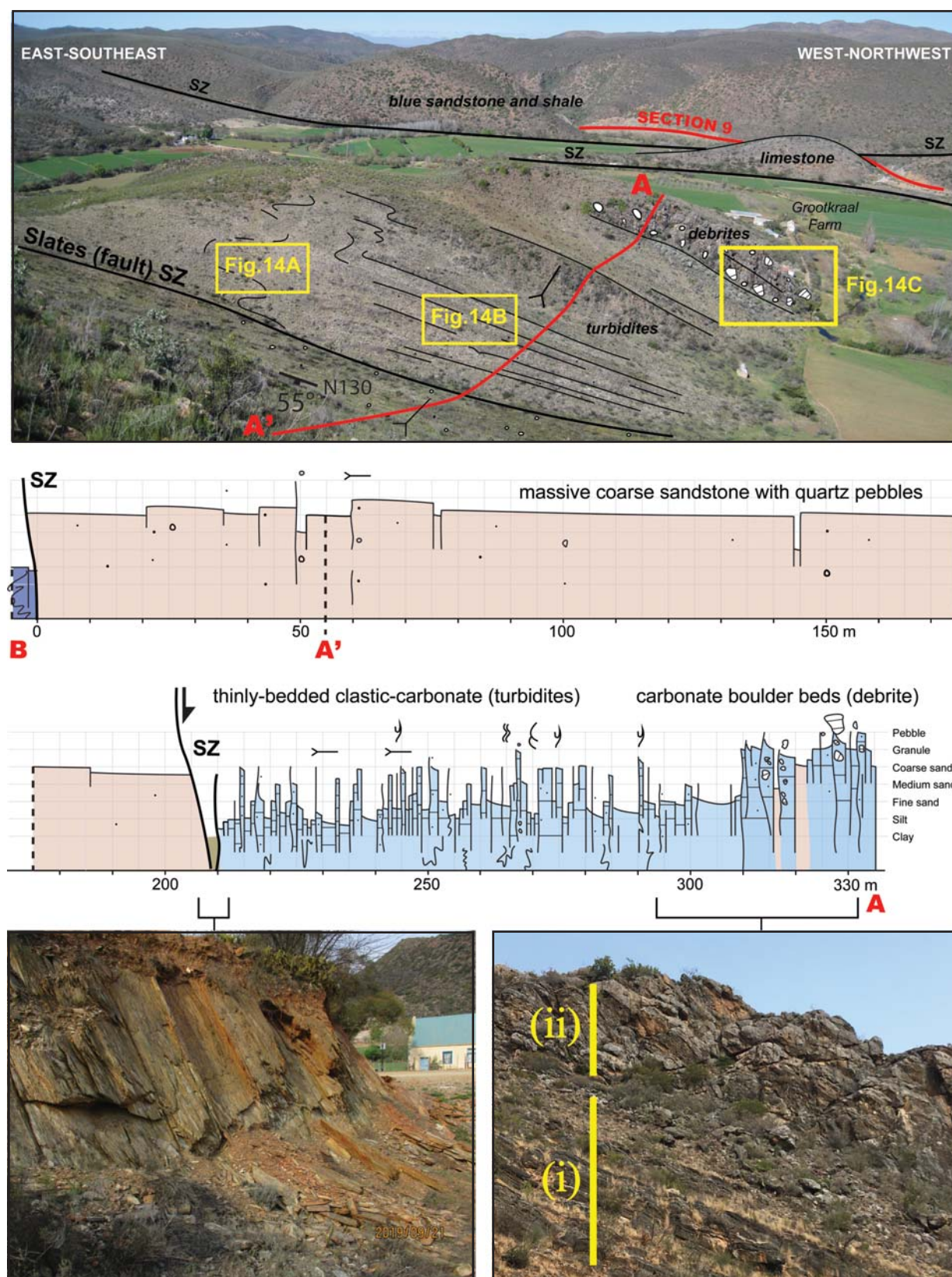


Figure 13. Section across Grootkraal Farm, 125 m thick clastic-carbonate rocks with sedimentary structures that indicate younging directions to the south, becoming thicker bedded upward and passing into carbonate boulder beds interpreted as turbidites and debrites (Fig. 12 for location). A 50 m thick schist zone (SZ, bottom left) marks the lower tectonic contact, and in turn is overlain by (bottom right) younging-upward sequences of carbonate turbidites (i) and carbonate boulder and sandstone beds (ii); for detailed outcrops see Figure 14A–D.



Figure 14A. Examples of steeply plunging folds within the layered clastic-carbonate rocks in the southern part of Section 3 (Fig. 12 for location). (a–b) Open folds without axial planar cleavage; (c) tight folds with variable axial planar shear zones (blue lines); and (d) open fold with folded tectonic calcite zones parallel to bedding that likely represent pre-fold shear zones (compare to Fig. 4A).

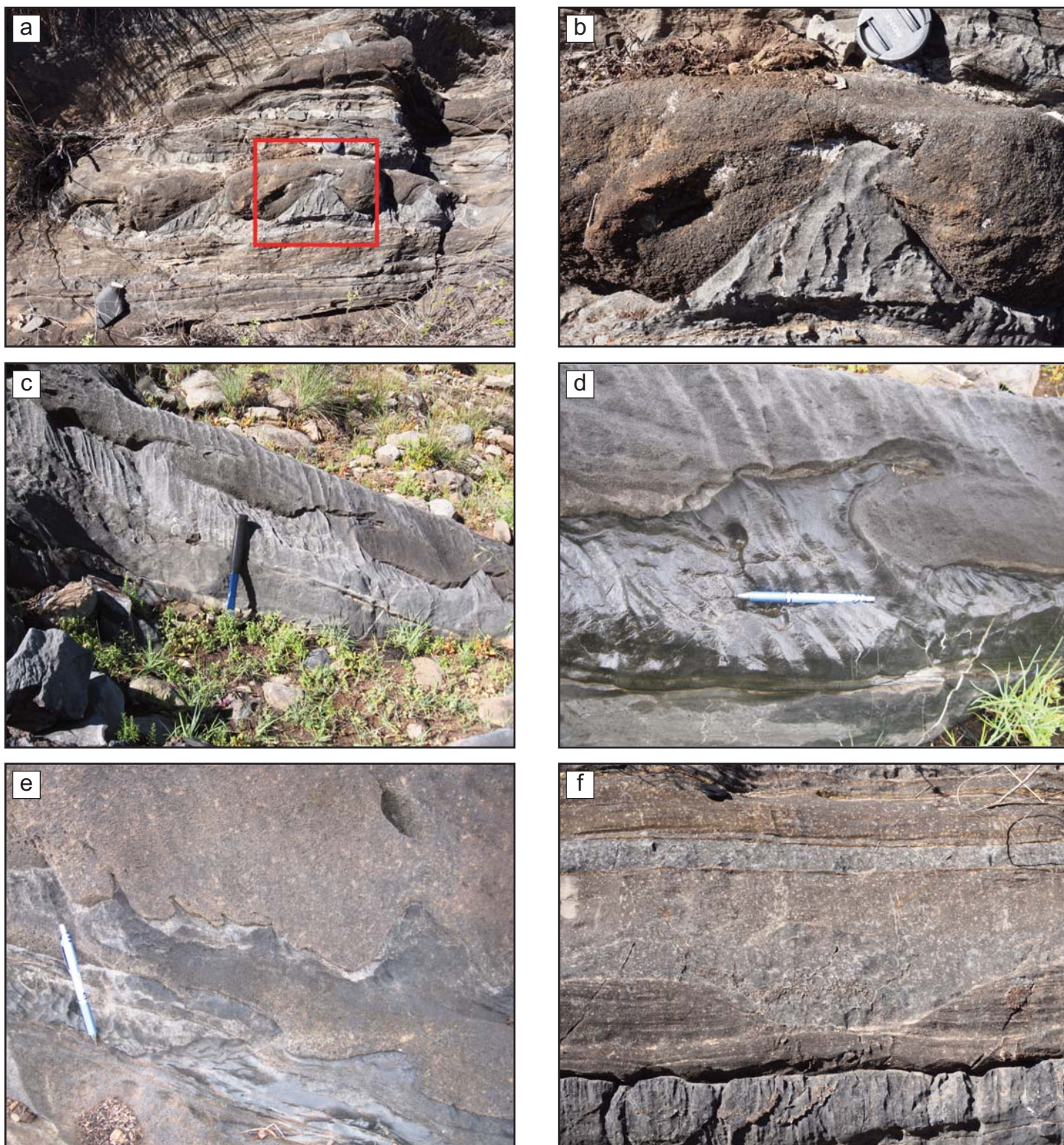


Figure 14B. (a–e) Soft sediment deformation (flame) structures within the limestone turbidites (brown = coarse-grained; grey = fine-grained); and (f) erosion channels (contourites). All structures confirm younging directions to the south (Fig. 13 for location).

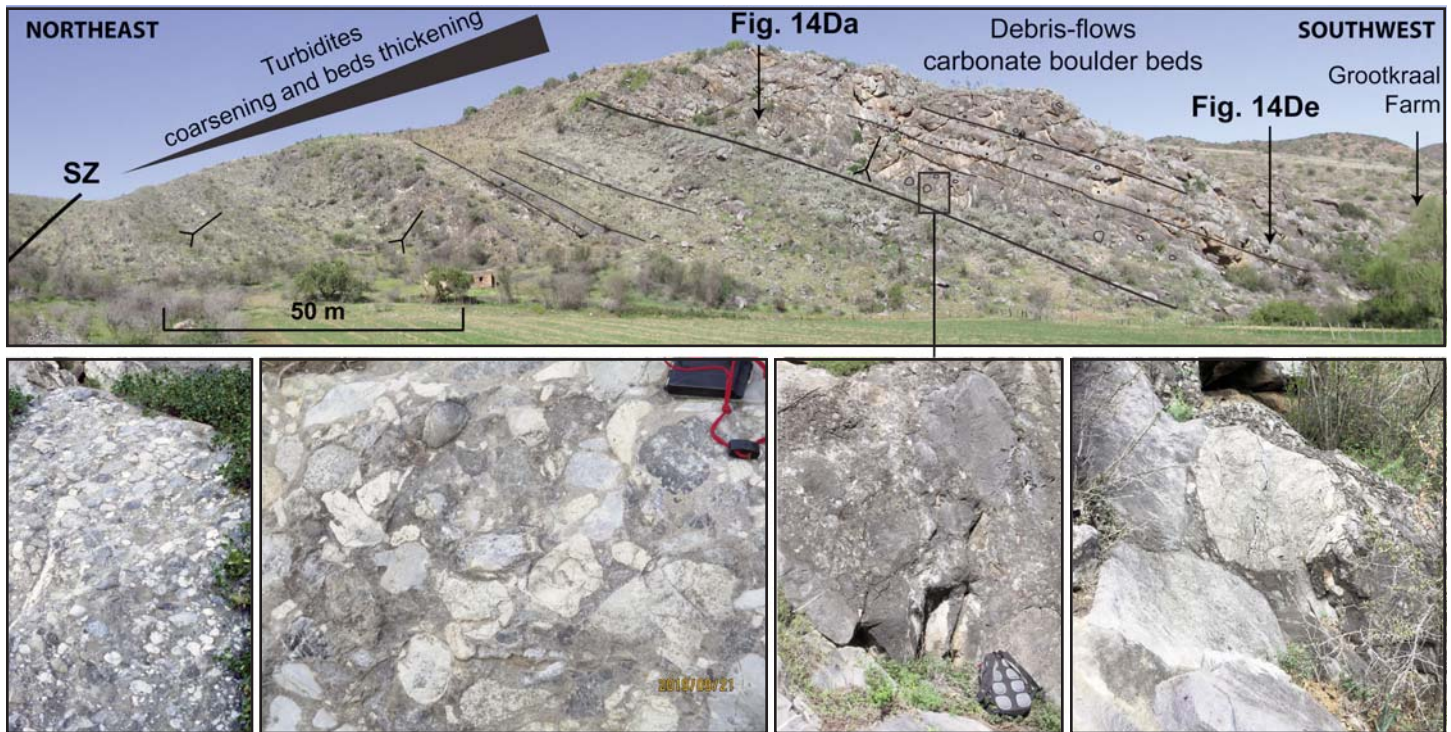


Figure 14C. Sequences of clastic-carbonate rocks are sharply overlain by thickly bedded boulder conglomerate and coarse quartzitic sandstone. The succession dips 40° to the north and contains erosion surfaces and large rounded to angular limestone boulders interpreted as debris flows.

less foliated and reveal open folding with psammitic layers. At outcrop C, these rocks are intruded by subvertical felsic dykes (Fig. 22A). Zircons from two of these dykes (d1 and d2) yielded a U–Pb date of ca. 1084 Ma (Fig. 22B).

Farther west along the road, this section is structurally overlain by a thick isoclinally folded carbonate-marble sequence (highlighted in Fig. 4C). In detail, this entire section represents part of a highly deformed fold limb of the Kango Caves Group (shortened by at least 60%; see Map 2), which makes it difficult to separate the Kombuis from the Nootgedacht formations with confidence.

Section 7. Clastic-Carbonate Rocks at De Hoek Cave

Thick-bedded limestones within the Groenfontein Formation outcrop at De Hoek Cave (Fig. 23A). These are bluish grey, mud-supported carbonate rocks containing quartz granules and clasts that show both fining and coarsening-upward sequences (Fig. 23B). Rare erosion surfaces indicate a younging direction to the south. The logged section is on the northern limb of an anticlinal structure, unconformably overlying green shale with orange sandstone beds. It comprises 70 m thick fine-grained limestone overlain by 40 m thick clastic limestone that become thicker bedded and coarser upward. This succession suggests deposition by filling large channels and progradation.

Section 8. Interbedded Sandstones, Siltstones and Shales of Melville Dam

At Melville Dam (Fig. 24), interbedded sandstones, siltstones and shales more than 1 km across are repeated along east–west

relatively tight folds plunging south. The sedimentary facies are green to orange, fine to very coarse-grained sandstone beds, 10 cm to 1 m in thickness, alternating with siltstone and shale. The fining upward successions of coarse sandstone with erosional bases, passing upward into ripple cross-laminated siltstone and shale are characteristic of turbidites. Preserved groove marks indicate a northwest–southeast transport direction.

Section 9. Thrust Fault and Cross-bedded Sandstones Along the Main Road Near Kombuis

Flanking the main road near Kombuis (Fig. 25), a major shear zone (Boomplass Thrust) linked to 70 m of highly schistose phyllite of the Groenfontein Formation and 70 m of interlayered limestone/marble and phyllite of the Kombuis Formation, dips 65–80° south along this fully exposed section. To the north, this schist zone, unexposed for 30 m, links to zones of highly deformed marble boudins in schistose phyllite (described in Section 6). Southward, the shear zone is tectonically overlain by 260 m thick grey to blue cleaved sandstone, siltstone and greywacke of the Uitvlugt Formation (Fig. 26a) where, across the upper 50 m, the cleavage cuts across bedding of a well-preserved anticline linked southward for 200 m to separated parts of a highly fragmented synform along schistose phyllite (Fig. 26c).

The sandstone beds are overturned, comprising relatively abundant syn-depositional erosional features that indicate younging directions to the north (Fig. 25). The sedimentary facies include undular and large-scale cross-stratifications, 2–10 m in width, with mud drapes and rip-up clasts, which indi-

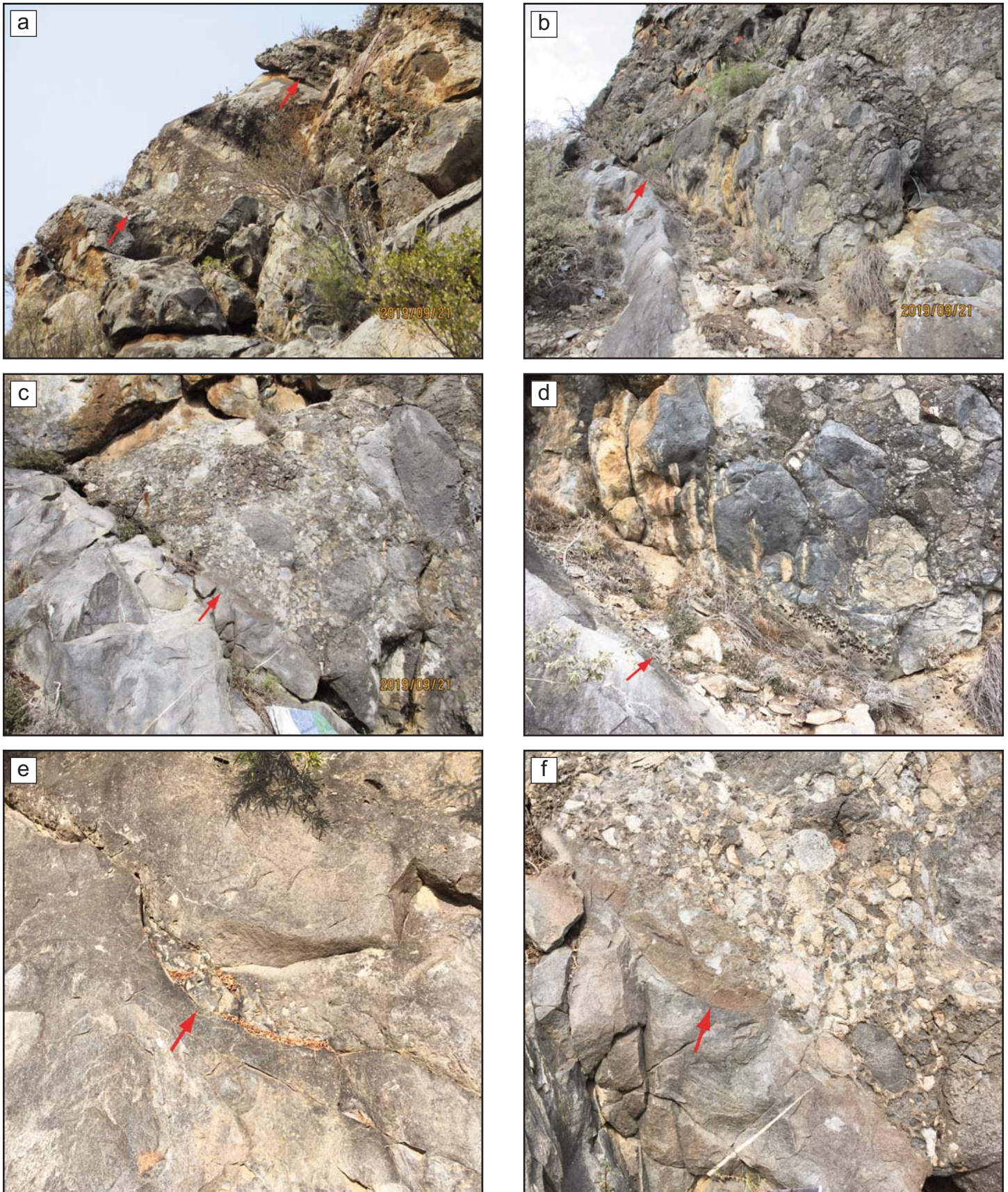


Figure 14D. Erosive contacts (red arrows pointing up) within the carbonate boulder beds indicating younging directions to the south (Fig. 14C for location).



Figure 15. General north-facing view across the lake of Koos Raubenheimer Dam (Section 4, Map 1), showing the location of detailed cross-sections along the western and eastern banks in Figures 16A and 16B, respectively.

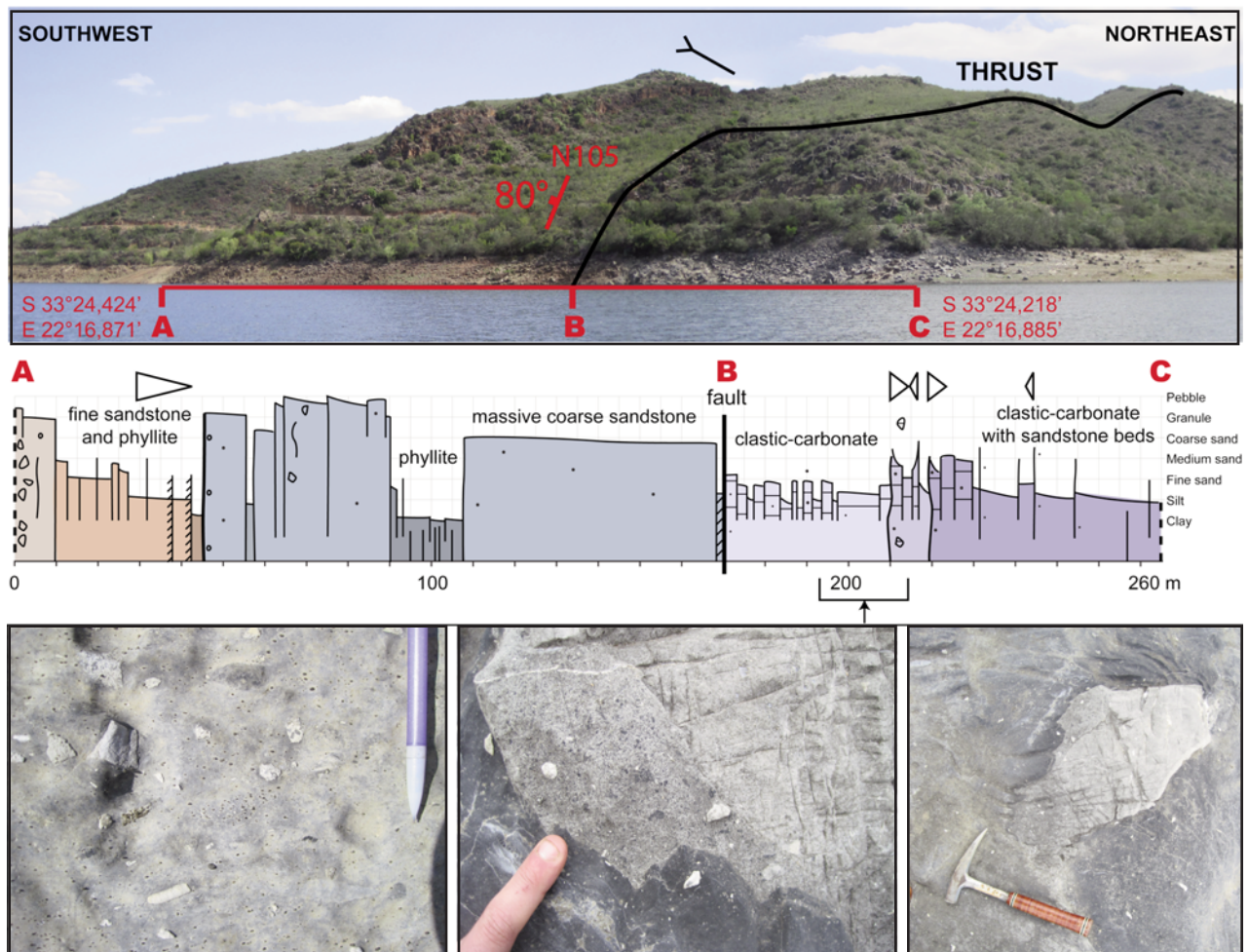


Figure 16A. Northwest-southeast cross-section and sedimentological log along the western bank of Koos Raubenheimer Dam (Fig. 15 for location). Conglomerate, sandstone and shale of the Nooitgedacht Formation are covered by clastic-carbonate rocks and shales of the Kombuis Formation.

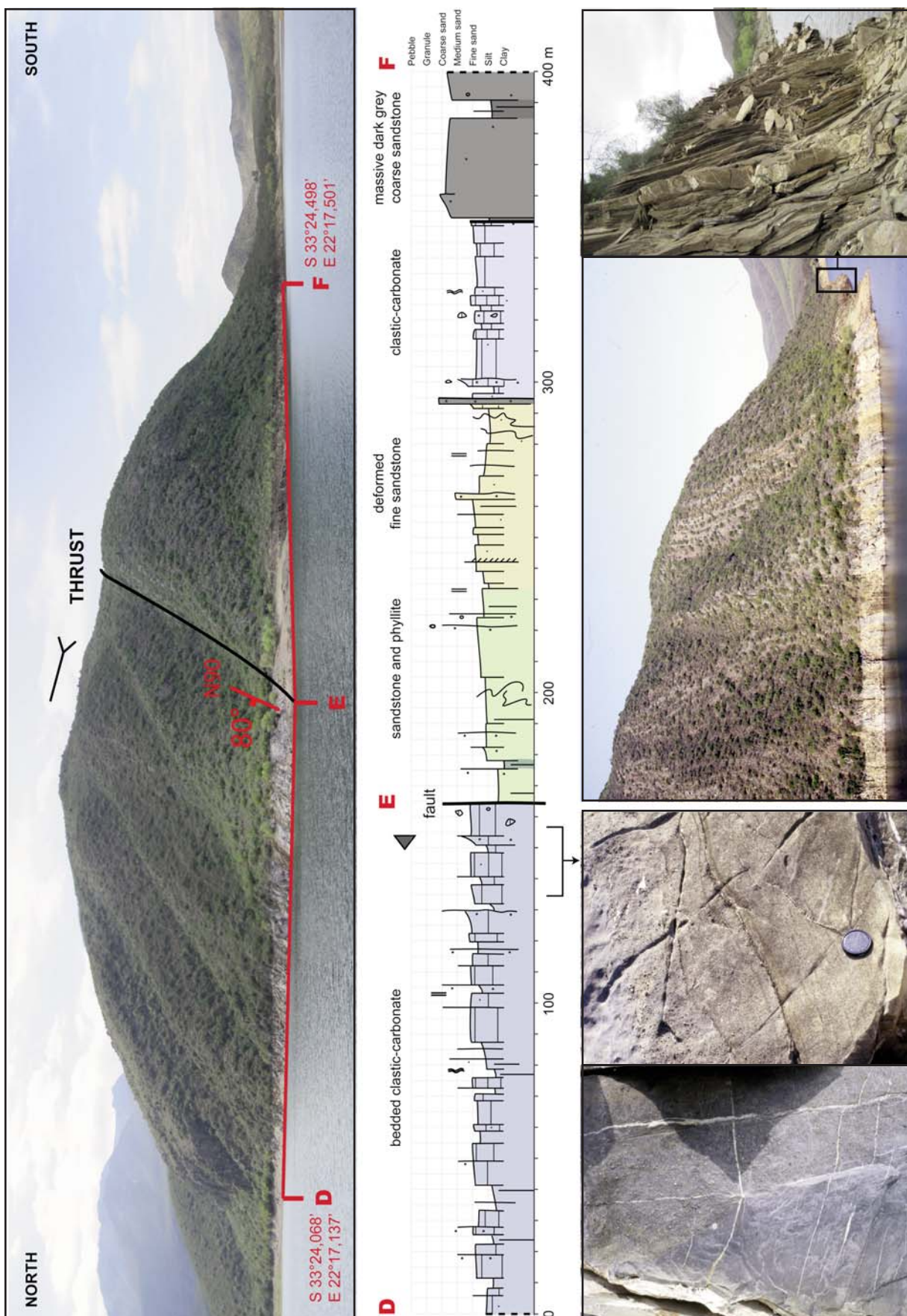


Figure 16B. Section of limestones and shales of the Kombuis Formation along the eastern bank of Koos Raubenheimer Dam (Fig. 15 for location). Sequences of coarse sandstone and phyllite with bedding-parallel cleavage and schistosity alternate with clastic-carbonate rocks and bedded limestones, which in places preserve sedimentary diamictite and graded clastic matrices (bottom left). Bedding-parallel cleavage in slate sometimes crosscuts sandstone beds to reveal direction of sub-isoclinal fold closures (bottom right).

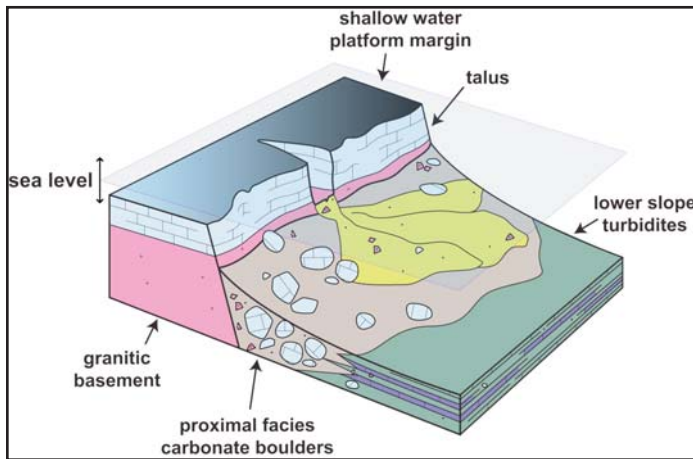


Figure 17. Schematic facies model of a submarine escarpment cut by a river section that deposited granite pegmatite and feldspathic sandstone/grit, limestone boulders and diamictite of the Kango Caves Group linked to variable sea-level changes. These carbonate sequences resemble the Lower Paleozoic marine sequences in Newfoundland, deposited across the Grenvillian basement of the Long Range Peninsula and from there eastward as far as Fleur de Lys (e.g. Figures 32–34 in James and Stevens 1986).

cate shallow marine deposition (Fig. 26b). These are underlain over ca. 2 km by similar, but less well-exposed subvertical sandstones and shales, cut by numerous internal shear zones and subvertical thrusts with fragmented phyllites (e.g. Fig. 26e).

The abundant bidirectional cross-bedding and flaser beds with laminated mud in the quartzite indicate rapidly changing low- and high-energy currents in an intertidal paleo-environment, such as for example sand flats in estuaries. Notably, no fossils or bioturbations have been observed anywhere in this section.

Section 10. Conglomerates and Sandstones Along Schoemanspoort

This north–south section (> 500 m across), previously called

Reitkloof (Map 1), is best exposed along the main road to Oudtshoorn flanking the Grobbelaars River near Ou Tol (Old Toll House). Southward from the Toll House entrance, the section comprises well-cleaved cross-bedded arkoses and blue quartzitic sandstones with pebbles and cobbles of the Vaartwell Formation (Fig. 27). The clasts are mainly of sandstone (intraclasts) and well-rounded granite pebbles between 5 and 30 cm in diameter. The shale/sandstone pebbles and cobbles are mostly flattened along the cleavage, while the granite boulders generally preserve their original shapes. The subhorizontal bedding shows open folds cut by a strong east–west striking subvertical cleavage that makes the identification of bedding planes challenging in many places. In coarse-grained sandstone, younging directions from cross-stratifications are to the north.

The section is intruded by several mafic dykes, now amphibolite, with vertical schistosity, commonly with deformed quartz veins (Fig. 5a), and similar to those dated at ca. 512 Ma in the eastern region of the Kango Complex (Haas 1998; Fig. 2b).

This quartzitic sequence is equivalent to the Kansa Group conglomerate that unconformably overlies the Groenfontein Formation of the Goegamma Group, and it is here interpreted as a molasse deposit (Fig. 3). The basal contact is well exposed in the mountain section about 200 m higher (Barnett et al. 1997) where U–Pb detrital zircon dates reveal a Cambrian age for the conglomerate (< 518 Ma), consistent with another detrital zircon date of ca. 485 Ma obtained from the Uitvlugt Formation (Naidoo et al. 2013). The age of the granite boulders is consistent with the age of the Saldinian (including Table Mountain) granite bodies (e.g. Scheepers and Armstrong 2002; Kirsters 2016; Miller et al. 2016).

Section 11. Subvertical Unconformity Between the Kango and TMG Rocks

TMG quartzite is coarse to fine-grained with quartz pebble

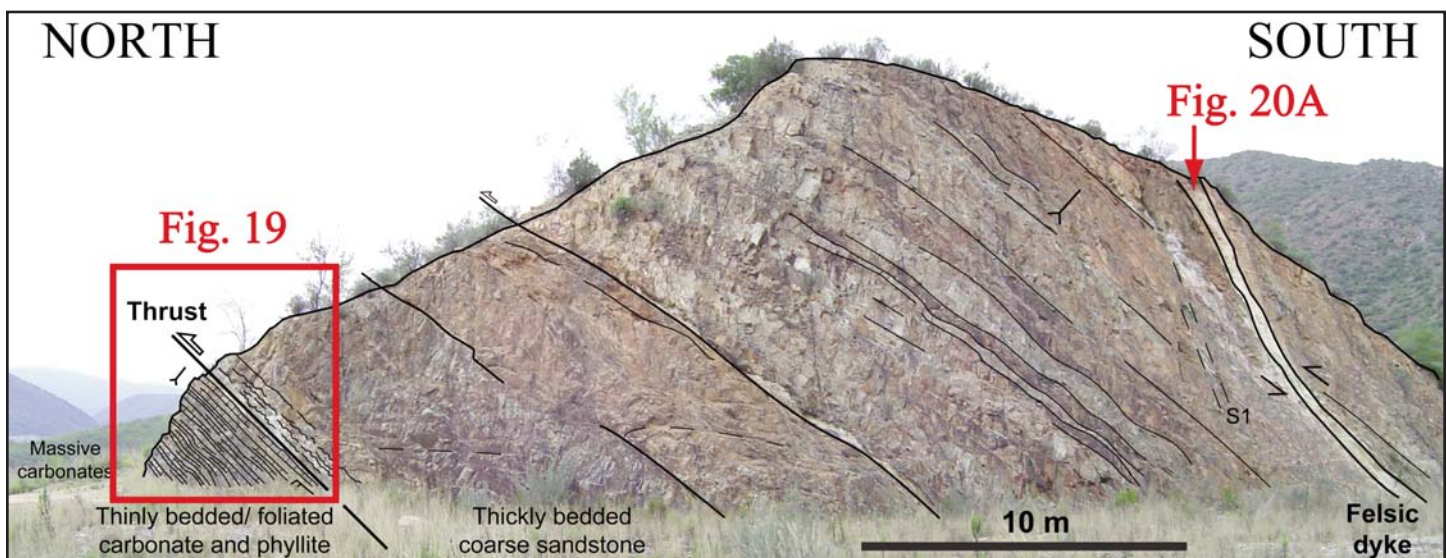


Figure 18. Thrust contact between clastic-carbonate rocks and coarse quartz sandstone dipping south, intruded by felsic dykes (Section 5, Map 1). Figure 20 presents the new geochronology.



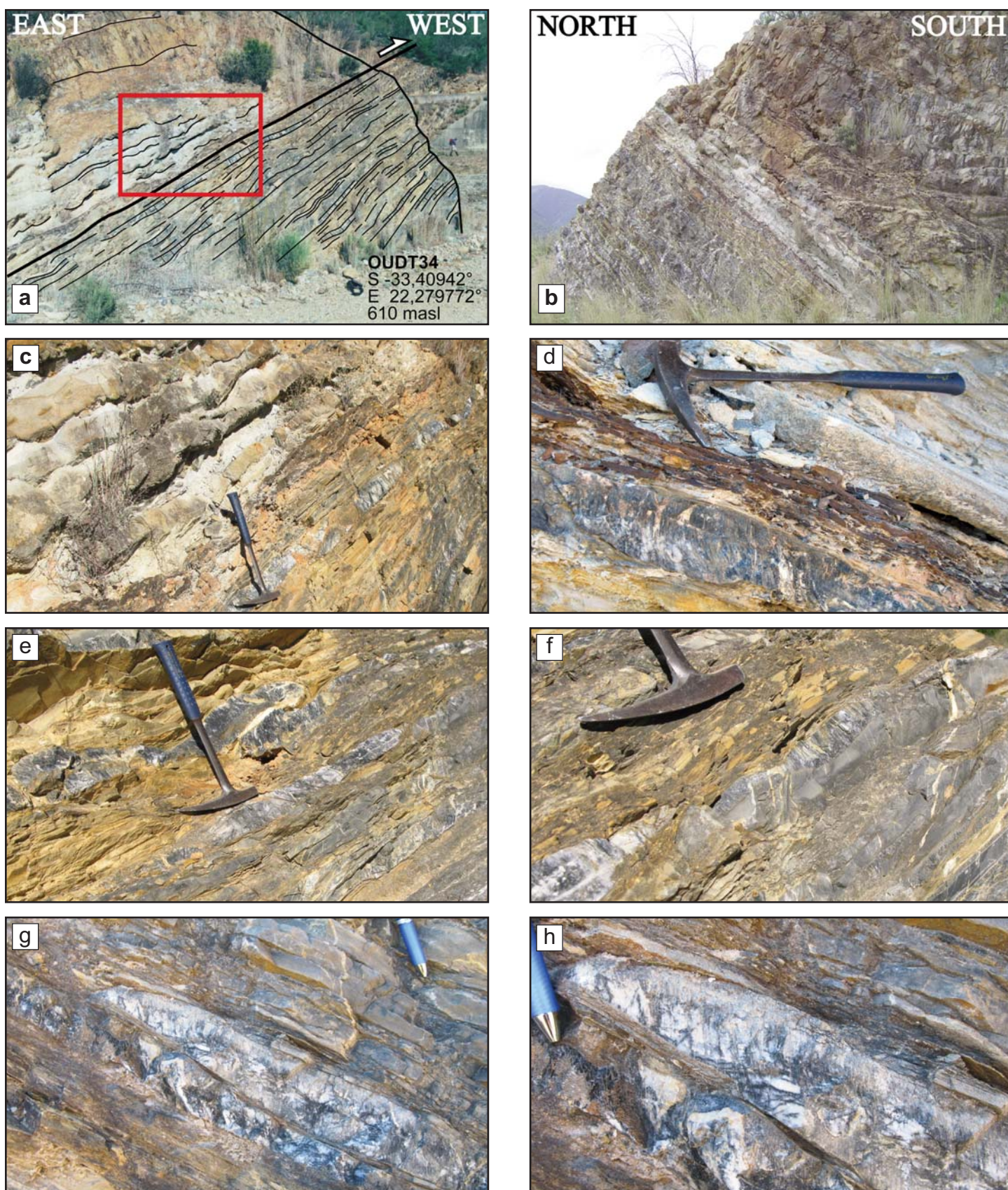


Figure 19. Along the thrust fault, thin limestone beds preserve extension veins that are duplicated – this is a complex thrust zone with episodic extensional carbonate veins (Fig. 18 for location).

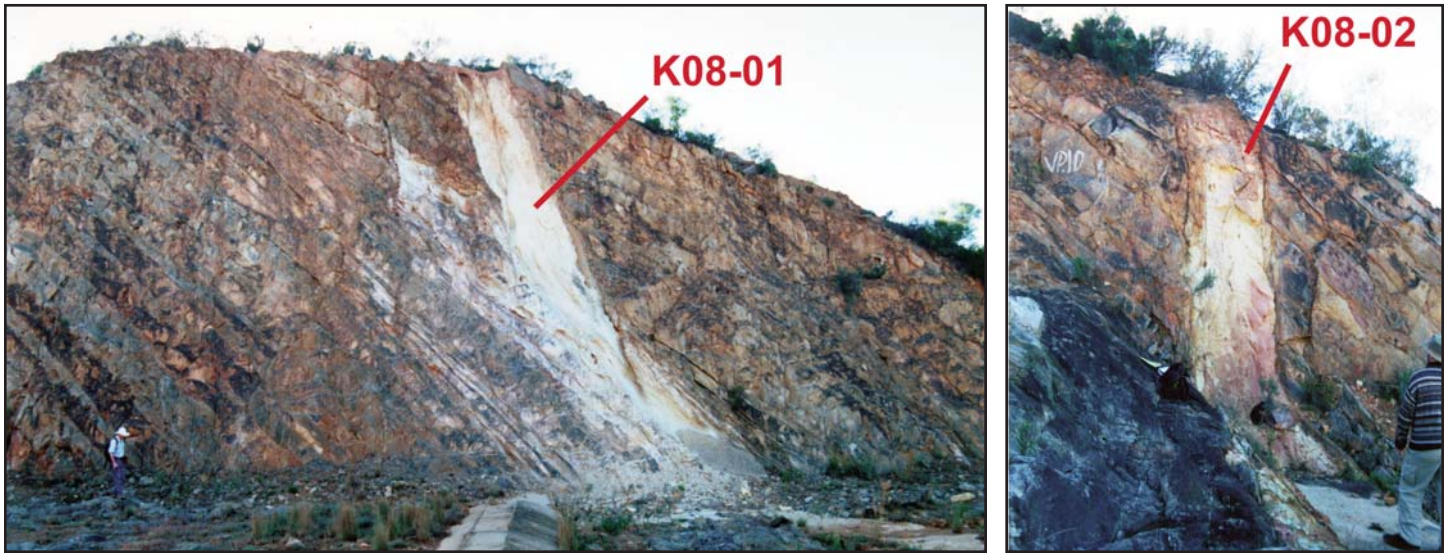


Figure 20A. South-dipping quartz sandstone (grey-red) of the Nooitgedacht Formation intruded by two steep dipping felsic dykes (white to pale brown) along the cut-off wall of the Koos Raubenheimer Dam (Fig. 18 for location).

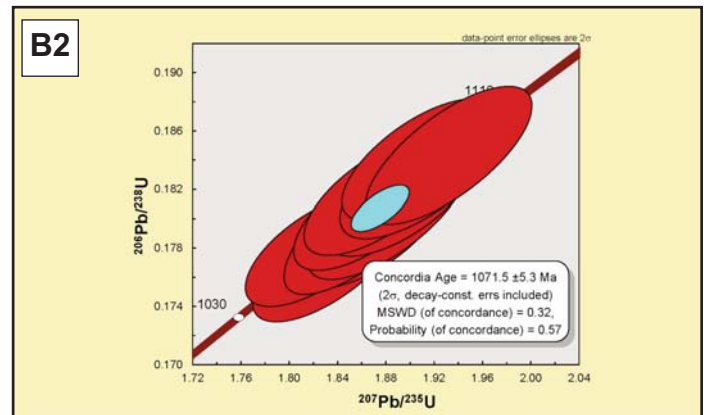
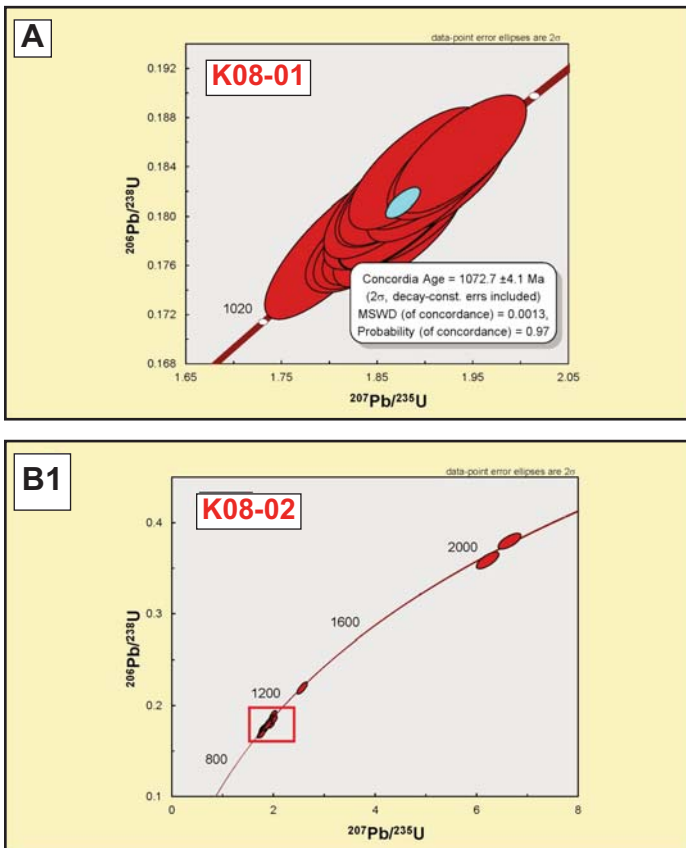


Figure 20B. U–Pb dates of igneous zircon grains from the two felsic dykes (K08–01 and 02; Fig. 20A) at ca. 1072 Ma are interpreted to represent the age of intrusion, and with ca. 2000 Ma inherited zircons (B1). Data are provided in Appendix (2s, decay-constant errors included).

conglomerates and dips from subhorizontal to steeply north (overturned) above the Kango sequences. Deformed unconformities are well preserved in local exposures (Map 2). In most sections, the TMG directly overlies schistose greywackes and shales of the Groenfontein Formation. However, in a small folded section of the studied area (Fig. 28a), Groenfontein greywacke is unconformably overlain by schistose con-

glomerates, sandstones and shales of the Schoongezigt (Gezinskraal) Formation, which in turn are unconformably overlain by quartzites and conglomerates of the TMG. This feature outcrops best in an open to close fold exposure, confirming that the main deformation across the Kango Complex is of post-TMG age, and thus likely linked to the Cape Fold Belt orogeny at ca. 252 Ma.

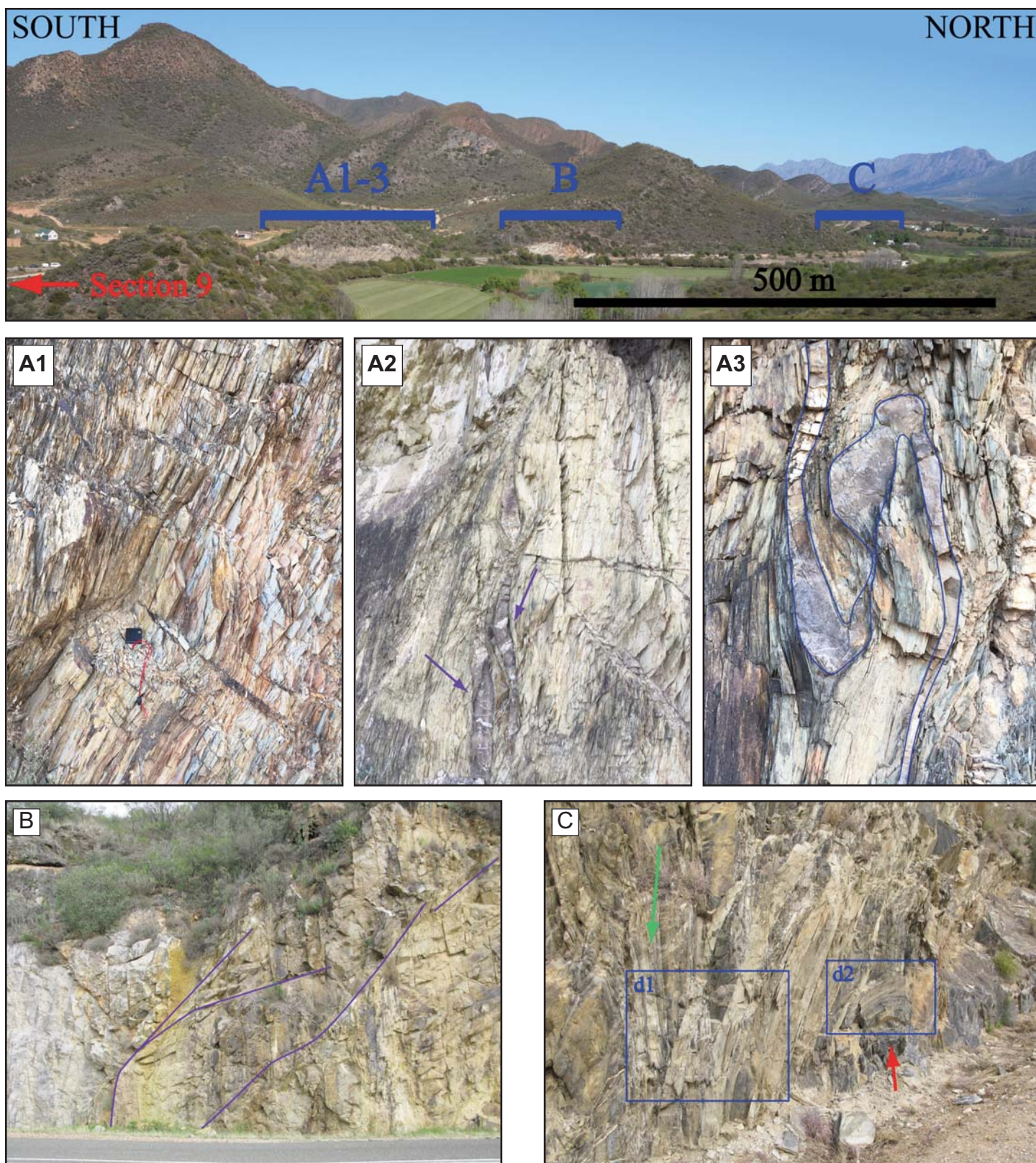


Figure 21. Section 6 of phyllites–psammites and foliated carbonate rocks of the Kango Caves Group; for location see Map 1. (A1) Phyllitic schist (pale yellow) with thin dismembered marble lenses, (A2) with limestone marble boudins and with isoclinally folded limestone lenses (blue-grey with white carbonate veins), and (A3) typical thin slate unit (dark grey with white quartz veins) duplicated within a thrust zone separating massive sandstone beds (pale grey). (B) Thrust between carbonate section (left) and phyllites–sandstones with thin grey carbonate limestone units (right and small thrusts within this unit). (C) Open fold of limestone (dark grey, red arrow) and subvertical limb of sandstone (green arrow), cut by steep dipping felsic dykes (d1 and d2 = highlighted in Fig. 22A).

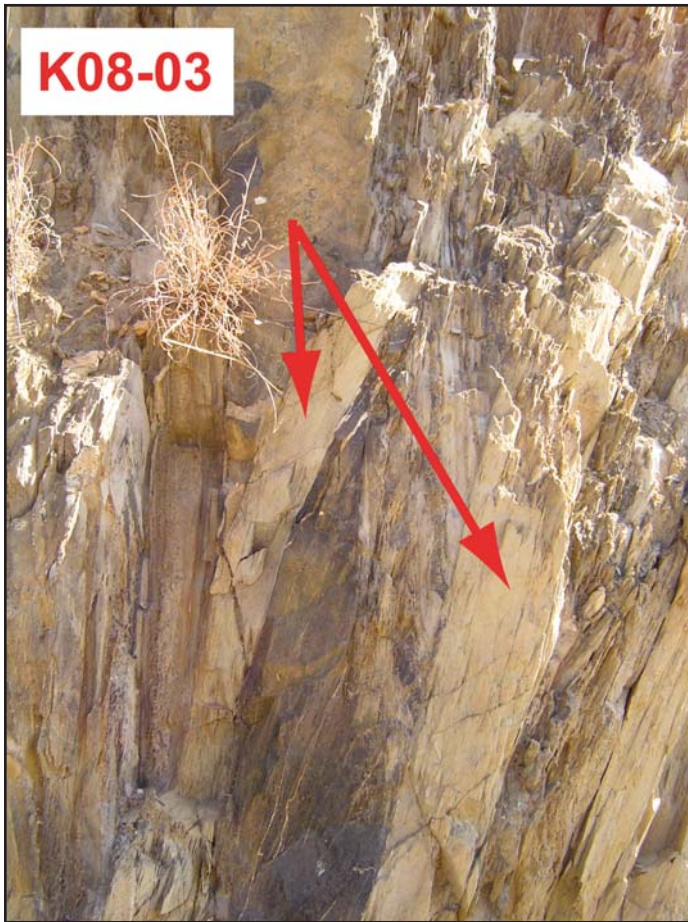


Figure 22A. Thin subvertical felsic dykes (red arrows) with parallel cleavage that is also axial planar to intruded subhorizontal open folded limestone (dark grey) and subvertical psammite beds (pale yellow), exposed 30 m below a major subvertical thrust zone (Fig. 4C).

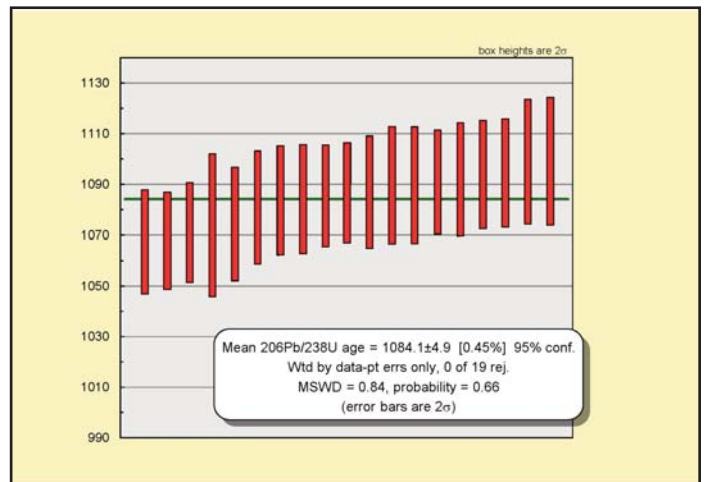
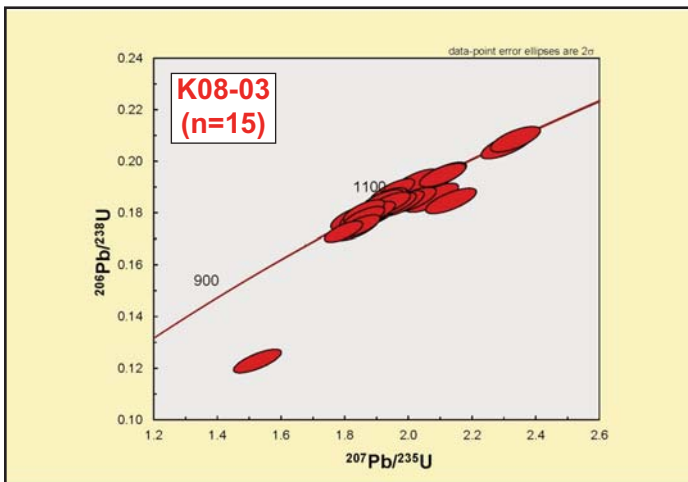


Figure 22B. U–Pb dates of igneous zircon grains from thin felsic dykes cutting a sequence of thin-bedded sandstone and limestone/marble of the Nooitgedacht Formation (Fig. 21C). The average U–Pb date of these felsic dykes (K08-03; Fig. 22A) is ca. 1084 Ma, which is 10 m.y. older than that of the Raubenheimer dykes, and very similar to the age of granitoids of the Spektakel Suite of the Khoisanland sub-province (e.g. Reid and Barton 1983; Joubert 1986; Reid et al. 1987). Data are provided in Appendix (2s, decay constant errors included).

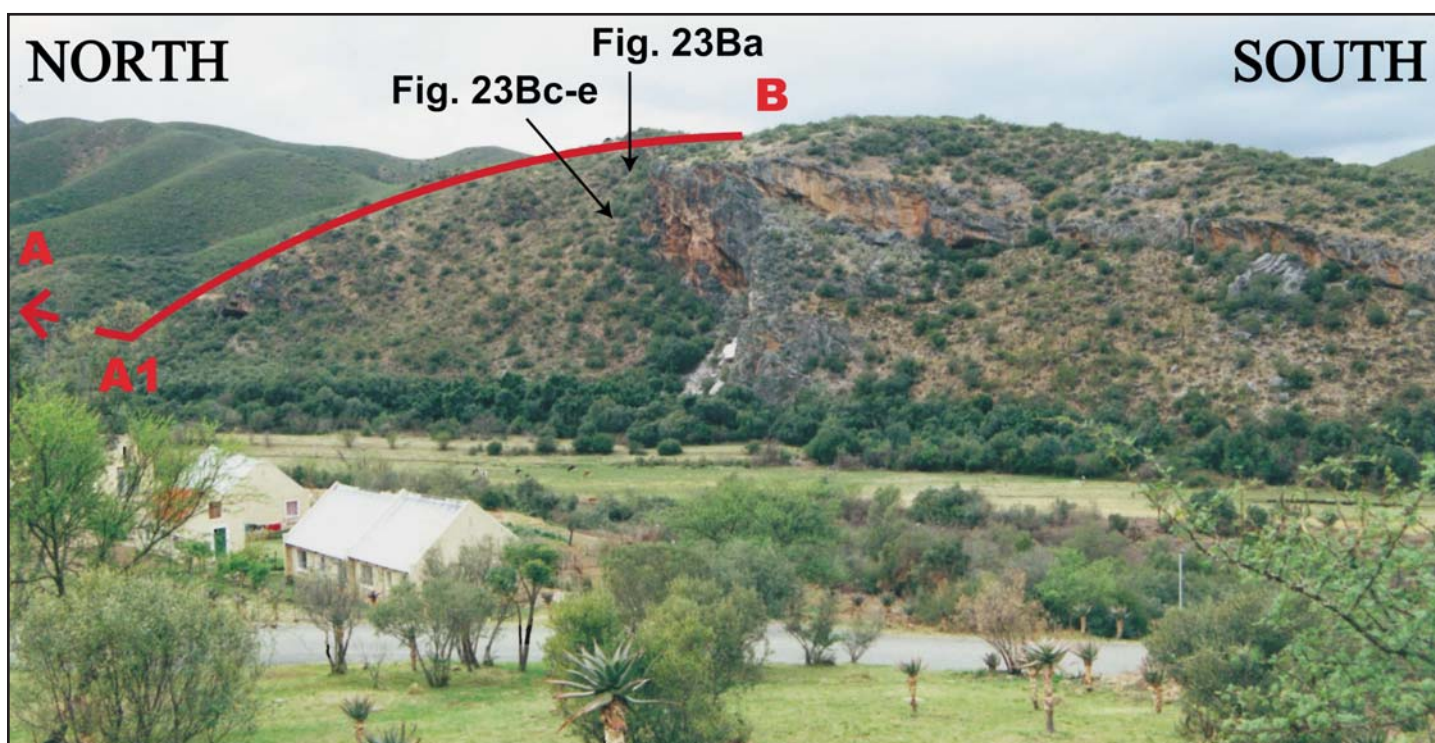


Figure 23A. Clastic limestone (orange weathering) about 100 m thick, exposed at De Hoek Cave near the Resort (Section 7, Map 1).

Frequently, highly schistose zones within the TMG, parallel to its bedding, are well exposed close to the contact with the Kango rocks (Fig. 28c–h), and shallow north-facing and folded thrusts are well exposed within the TMG well above the contact (Fig. 4E, and see below). Steeply dipping, axial planar cleavage is well developed in open folded shale of the Goegamma Group, and reveals a near parallel bedding between the two groups (Fig. 28b).

Section 12. Subhorizontal Unconformity Between the Kango and TMG Rocks

Stretching some 2 km south from the subvertical dipping contact between the Kango and TMG rocks along the Swartberg Range, two sections of subhorizontal bedded quartzite of the TMG outcrop unconformably across the Groenfontein shales and sandstones (Fig. 29). The Groenfontein Formation has a subvertical cleavage or schistosity linked to open well-spaced subvertical fractures in the overlying quartzite. The bedding orientations of shales across these outcrops are part of open folded subhorizontal sequences.

This subhorizontal section of TMG covering the Kango Complex is only very locally preserved, but the TMG outcrops across the entire study area in the west (Fig. 30). Here, the shallow dipping contact across the southern margin is overlain by a thrust duplex of TMG quartzite, with a total early subhorizontal shortening of about 75%. This is similar to thrust zones across the subvertical, but poorly outcropping TMG quartzite flanking the southern margin of the eastern Kango Complex (Map 2).

GEOMORPHOLOGY

Cretaceous to Present Erosion Rates

Rounded boulders of TMG quartzite cover remnants of the old flat regional topography preserved at ca. 1000–700 m asl, above the Kango sequences (Fig. 31). The onset of subsequent deeper river erosion implies that climate variation created an opportunity to open caves from the top of these flat surfaces along the subvertical contacts of limestone-marble with pelitic schist and sandstone of the Nooitgedacht Formation, linked to small rivers that eroded down to about 600 m asl (Decker et al. 2013). Similar caves occur along the contact of the Kango Caves Group conglomerate with the Groenfontein pelite-psammite units (for all caves location see Map 2).

Erosion rates changed considerably from ca. 100–200 m/m.y. during the Cretaceous (140–80 Ma), based on apatite fission track analyses (AFTA) on deep borehole samples just north of the Swartberg Mountains, to less than ca. 10–20 m/m.y. in the Cenozoic around 60–30 Ma; and, less than ca. 3–6 m/m.y. over the last 5 m.y., based on measurements of three river systems in the study area (Fig. 2b). Thus, the deep valleys across the Kango rocks are not due to the slow erosion during the relatively dry recent climate (e.g. Flowers and Schoene 2010; Scharf et al. 2013; Kounov et al. 2015; Evans 2015 and references therein). The origin of the Kango Caves may therefore link to high precipitation times before 60 Ma, and the formation of stalagmites during significantly reduced precipitation periods, as confirmed by their oldest known age of about 200 ka (de Wit et al. unpublished).



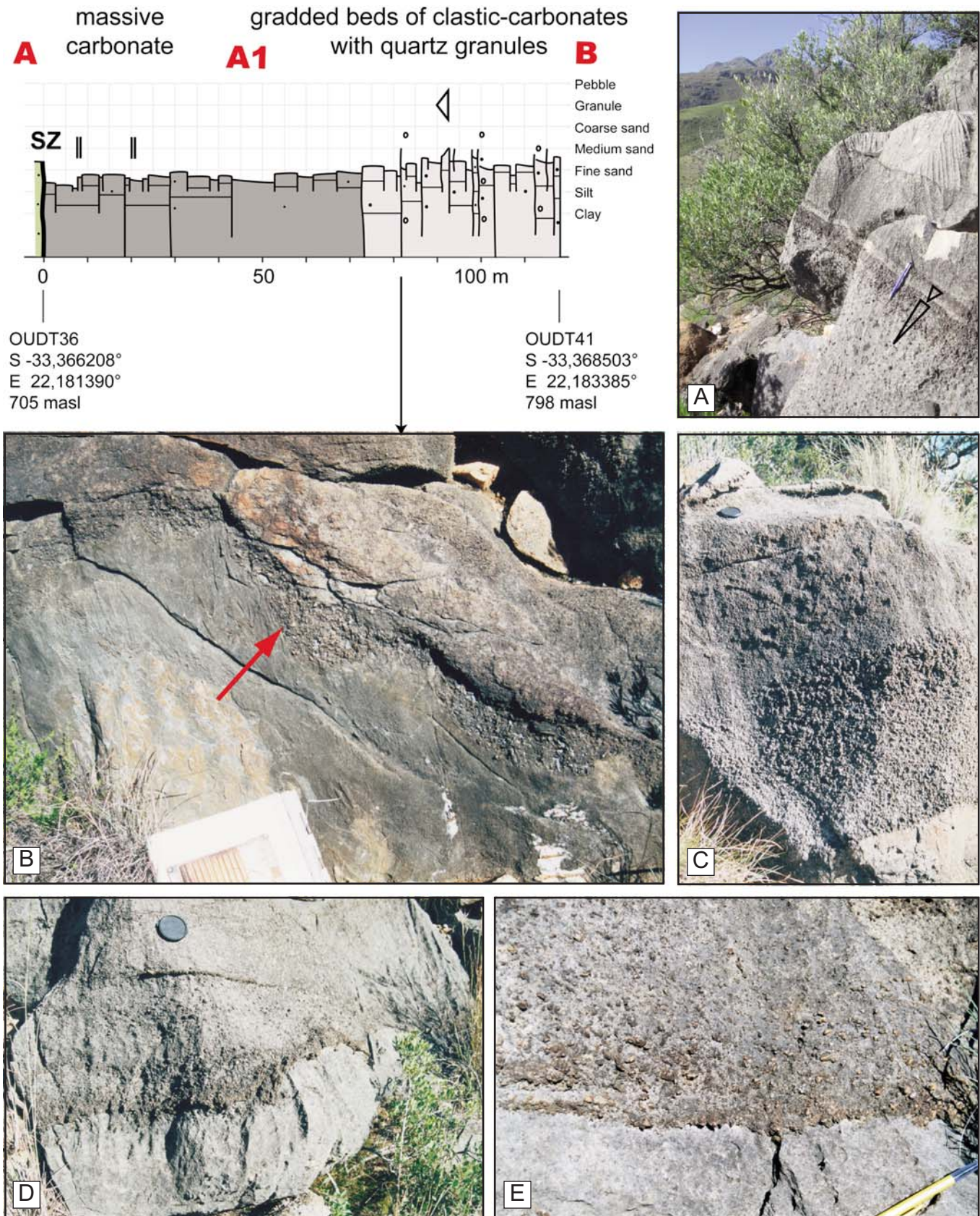


Figure 23B. The sedimentary log highlights a 120 m thick succession (Fig. 23A) that preserves both fining-up and coarsening-up graded beds of limestone (grey) with granule to gravel-sized quartz (brown). Erosion surfaces (red arrow pointing up) indicate younging to the south.

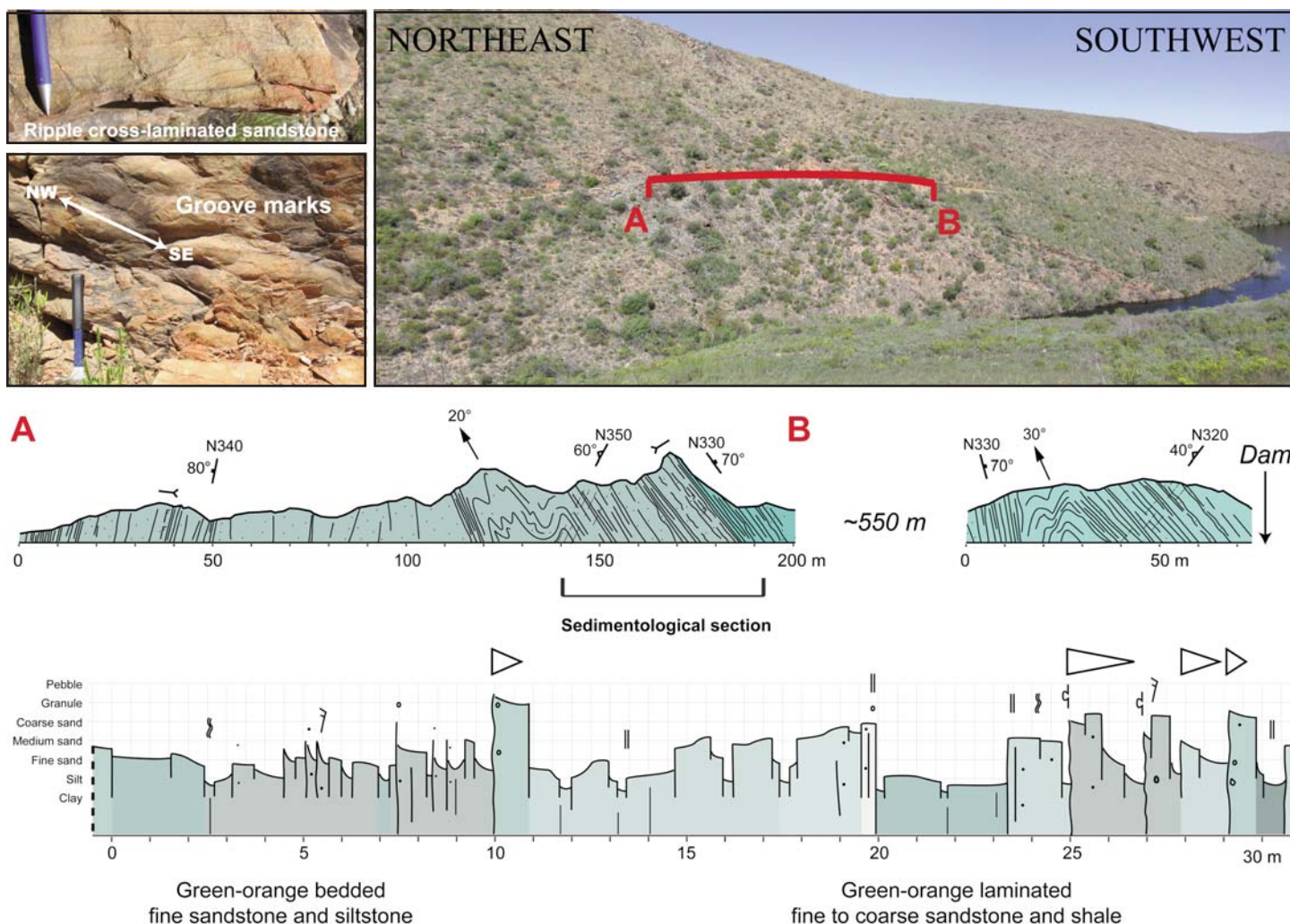


Figure 24. Northeast-southwest cross-sections and sedimentary log along the banks of the Melville Dam (Section 8, Map 1). Green and orange, fine to very coarse-grained sandstone, siltstone and shale of the Groenfontein Formation are characteristic of turbidites and show north-verging folds.

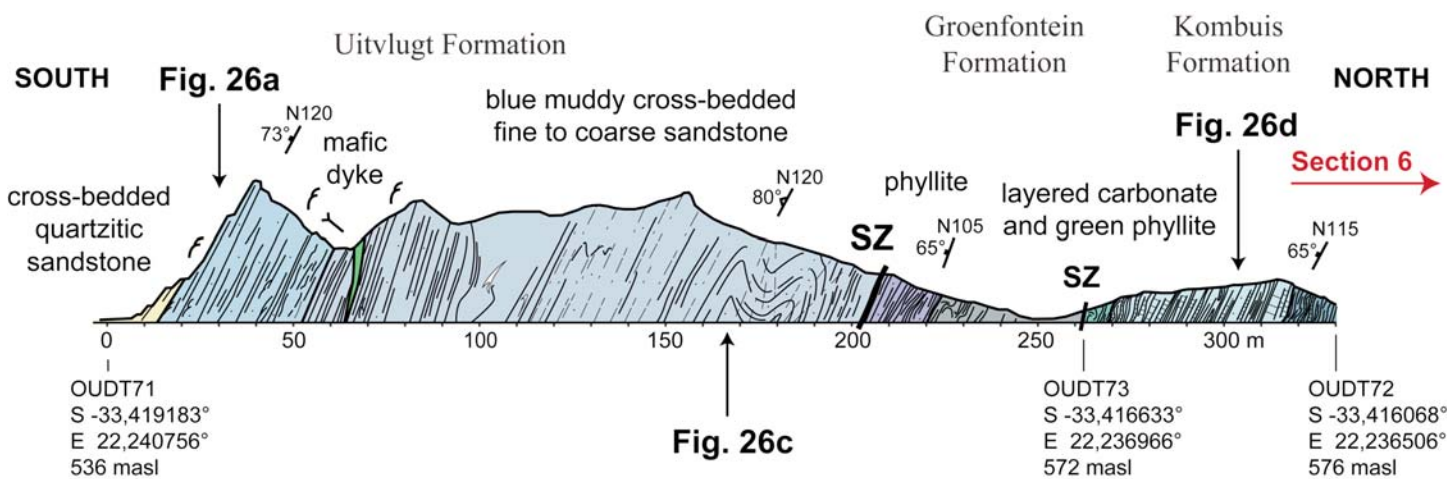


Figure 25. North-south cross-section more than 300 m long along the main road near Kombuis (Section 9, Map 1).



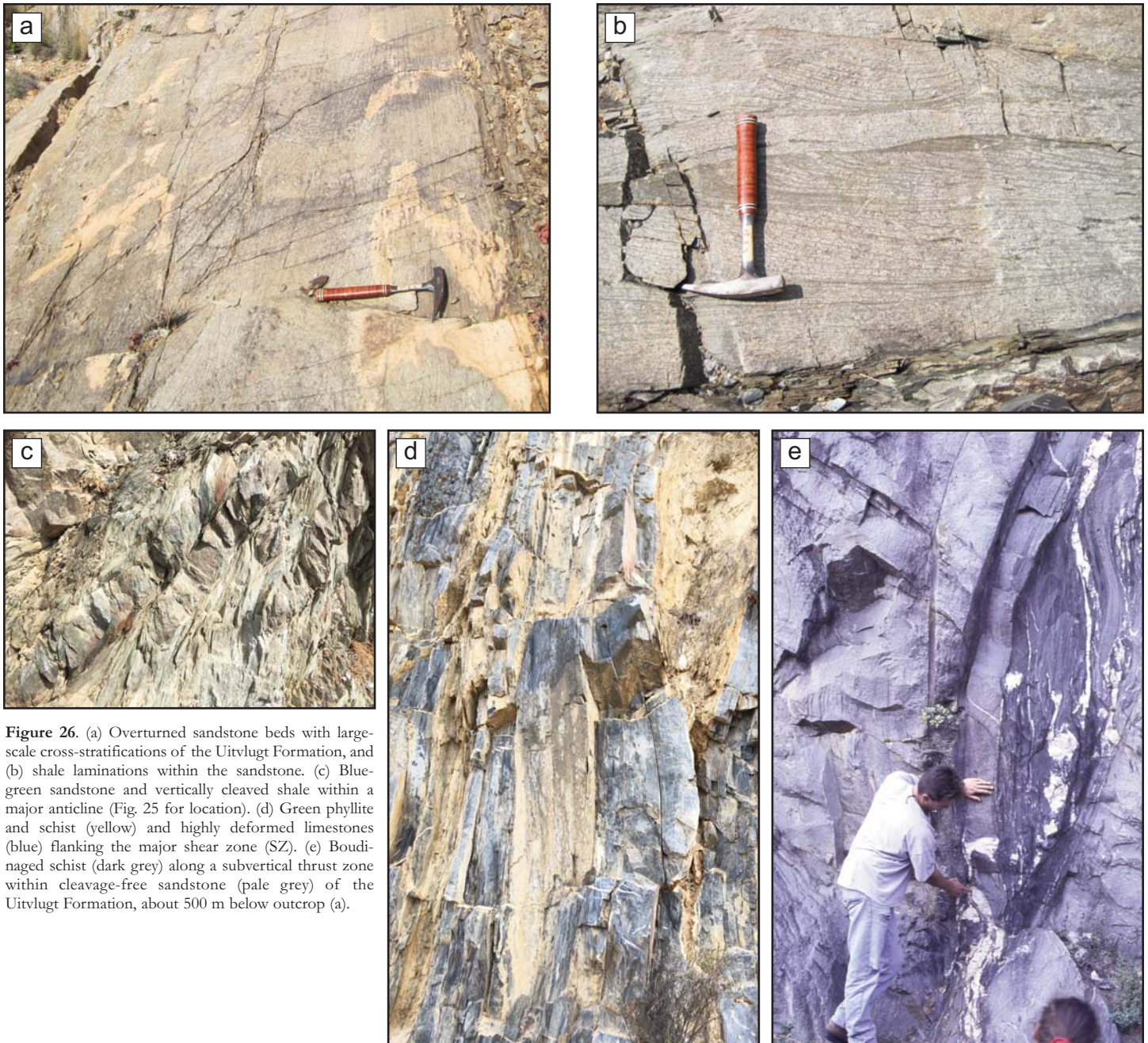


Figure 26. (a) Overturned sandstone beds with large-scale cross-stratifications of the Uitvlugt Formation, and (b) shale laminations within the sandstone. (c) Blue-green sandstone and vertically cleaved shale within a major anticline (Fig. 25 for location). (d) Green phyllite and schist (yellow) and highly deformed limestones (blue) flanking the major shear zone (SZ). (e) Boudinaged schist (dark grey) along a subvertical thrust zone within cleavage-free sandstone (pale grey) of the Uitvlugt Formation, about 500 m below outcrop (a).

Caves Flanking the Contact of Limestones with Greywackes

Karst topography and linked caves near the contact between the carbonate rocks of the Kombuis Formation and the pelite-psammite units of the Groenfontein Formation have been described by many field geologists; and while the paleodeposition system along this contact has been debated, all described the contact as an unconformity (e.g. Le Roux 1977, 1983, 1997; Le Roux and Gresse 1983; Gaucher and Germs 2006; Praekelt et al. 2008; Nel et al. 2018).

The best preserved evidence of such an unconformity is within the major fold closure exposed in the centre of the studied area where the unconformity surface dips steeply (Map

2). By contrast, the contact between these two formations along the fold limbs is cleaved and highly deformed along vertical shear zones, and most of the direct relationship between schistose shales and carbonate rocks is poorly visible and eroded, with the carbonate rocks being slightly more elevated at present (Fig. 32a).

The tectonic contact is commonly flanked by a section of carbonate conglomerate near the top of the Kombuis Formation along which at least five sinkhole localities are well-preserved (Fig. 6). Only one of these sinkholes is open deep below surface, and often explored by cavers who assume it to be linked to the Congo Caves via subsurface groundwater systems. All others are filled with sand and, at least at surface, with

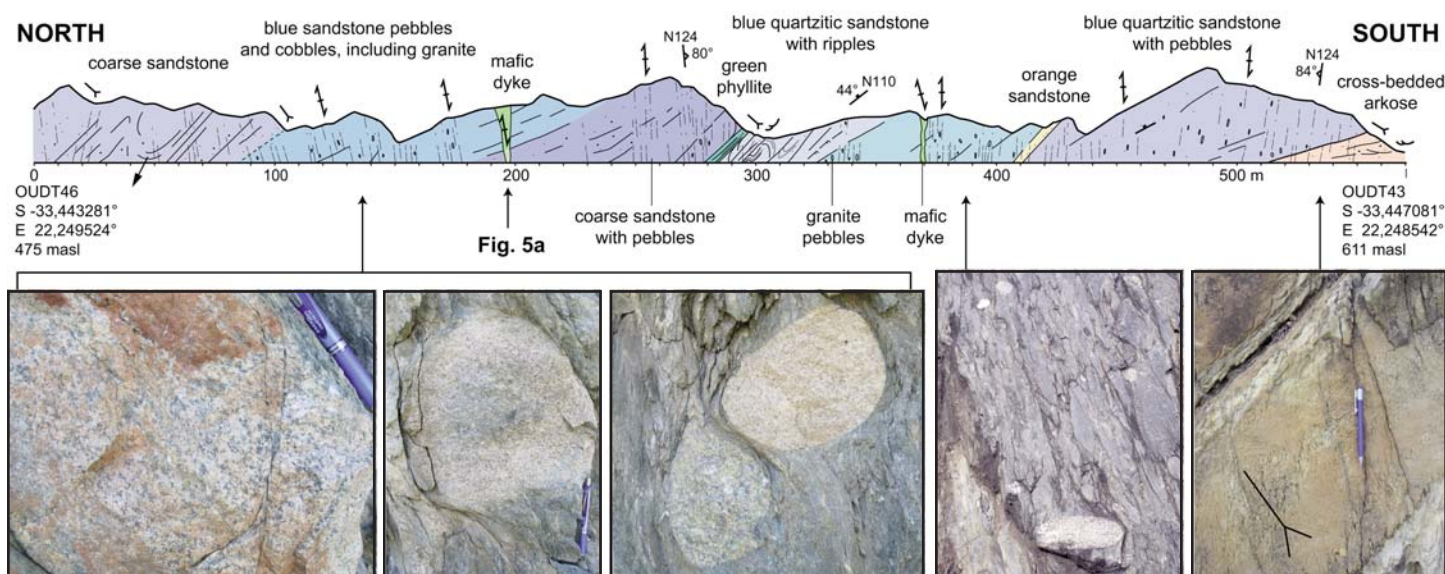


Figure 27. North-south cross-section of variably deformed/foliated conglomerates and psammites (sandstone) near Schoemanspoort (Section 10, Map 1). Well-rounded granite pebbles and cobbles remain resistant against the subvertical phyllite of the greenish blue pelitic psammite (left), compared to highly elongate sediment boulders (second right). In less deformed sections, graded sandstone beds with cross-stratification (right) confirm upward grading and define local open folds axis. These sequences are older than the 512 Ma basic dykes, and the granite blocks are likely linked to the Cape/Saldanian batholiths exposed along the western and southern coasts (Fig. 2a and cross-sections below).

quartzite boulders and pebbles, fragments of carbonate rock, and in places covered by iron precipitate (Fig. 32b–d).

We interpret these karst structures as relatively recent sinkholes likely filled during the early erosion of TMG quartzite, perhaps linked to glaciation–deglaciation of the Swartberg Mountains. By contrast, Praekelt et al. (2008) interpreted these sinkholes as paleokarst structures and paleovalleys filled with Neoproterozoic glacial deposits along the unconformity on top of the Kombuis carbonates, and fossilized by the Groenfontein turbidites. This interpretation is based on purported Late Ediacaran architarchs across the surface sinkholes mentioned above, and the fact that this paleokarst topography reveals development of subaerial unconformities (Gaucher and Germs 2006; Praekelt et al. 2008; Naidoo et al. 2013; Nel et al. 2018). While the biological affinities of architarchs cannot be determined with certainty, they may have been previously linked to stromatolites along the contacts between shale and carbonate. It is also possible that these are recently eroded stalagmites and carbonate precipitates, which are at present abundantly preserved in and around the Congo Caves.

Until more detailed analyses of these artefacts are provided, they remain in the realm of pseudo-fossils, especially as the (now deformed) unconformity contact between these sequences predates the deposition of the Goegamma Group (> 670 Ma; Fig. 33). Similarly, the existence of Neoproterozoic microfossils at the Congo Caves is unlikely, since the limestone is highly deformed (Fig. 7) and intruded by Mesoproterozoic felsic dykes (Fig. 22).

SYNTHESIS OF KANGO STRATIGRAPHY AND LANDSCAPES

Below we summarize the stratigraphy and landscape evolution across our study area (Fig. 33), and use these data to recon-

struct simple models for the deposition and erosion history (Figs. 34 and 35).

The complete section across the central Kango Complex, close to the Congo Caves (Map 1), has a stratigraphic thickness of some 10 km that covers a time span of 700–800 m.y. The section contains at least 50% phyllite, suggesting a thickness of at least 20–30 km before tectonic compression. However, folding into a near isoclinal system across this section halves the stratigraphic thickness to some 10–15 km, which appears reasonable if somewhat simplified without evaluating changes linked to the many thrust systems that have affected the area.

Many dated detrital zircons between 2.0 and 0.9 Ga recorded in the Kango sequences are likely derived from Mesoproterozoic basement that directly underlies this series (Fig. 2a). The (non-exposed) basement in the southern extremity of Africa is not Pan-African in age, as widely assumed, but most likely Namaquan (Grenvillian in age), ranging between 1.3 and 1.0 Ga (Hartnady 1969; Eglington and Armstrong 2003; McCourt et al. 2006; Lindeque et al. 2007; Stankiewicz et al. 2007; Linol and de Wit 2016).

Recent seismic and magnetic sections across the Cape–Karoo topography, including the present studied region, reveal relatively flat Namaquan basement between 5 and 10 km below surface. It is likely therefore that sediment was deposited in local basins after rapid erosion of the Namaquan sequences across western South Africa that were metamorphosed at relatively low-pressure granulite facies, followed by intrusion of late felsic magmatism at ca. 1.0 Ga (e.g. Waters 1986, 1990; Cornell et al. 2006; Cornell and Pettersson 2007).

The closest dates to compare with the age of the felsic dykes dated in this study are those from the Mesoproterozoic Kliphoek and Garies granites, which have dates of ca. 1078 ± 5 Ma (de Beer and Macey 2016a, b). These ages are within



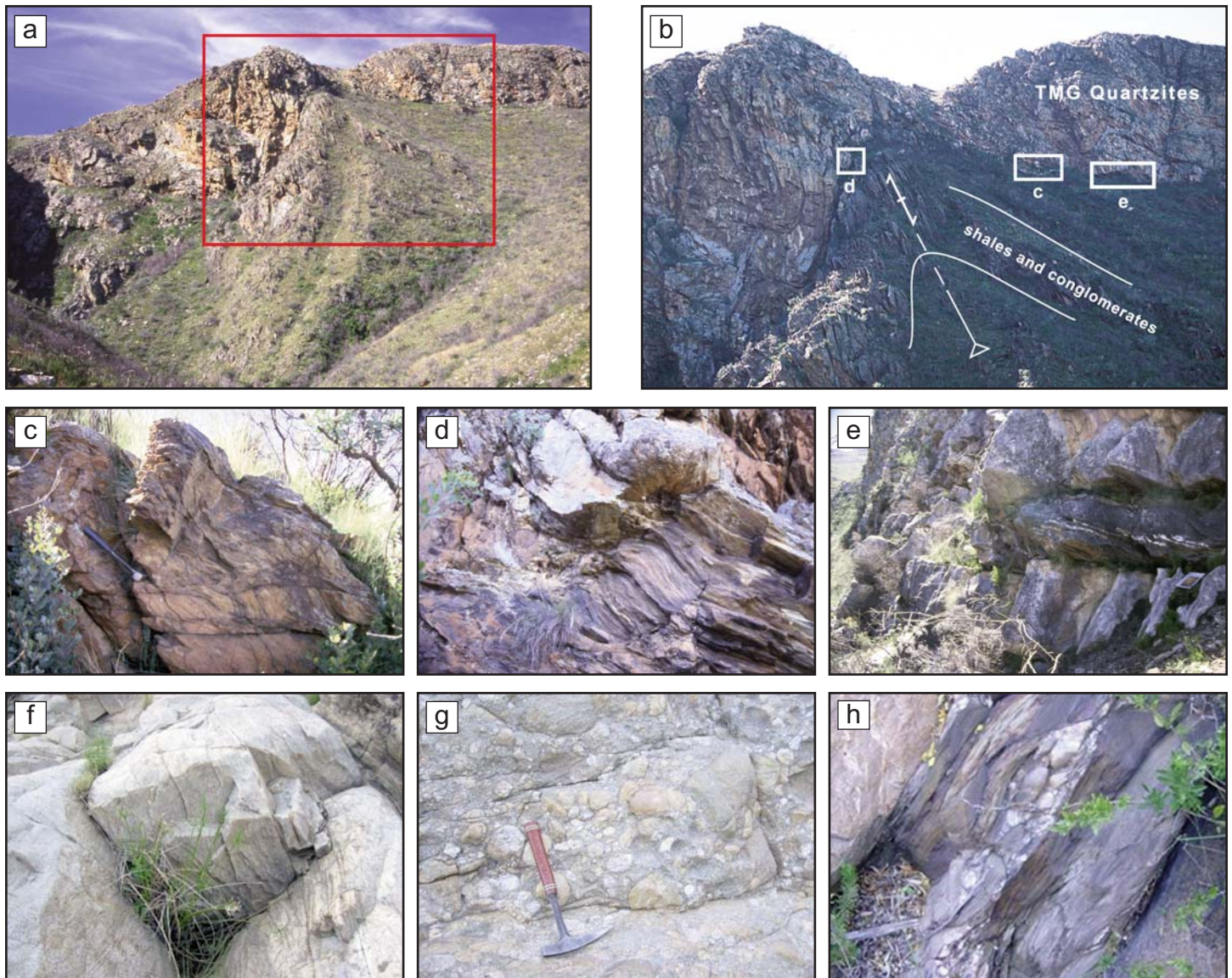


Figure 28. (a) Folded unconformity between the Goegamma Group and TMG quartzite (Section 11, Map 1), showing (b) the subvertical cleavage where slates of the Schoongezigt Formation are axial planar to a relatively shallow north-plunging open fold. Across this contact, TMG quartzite is cut by widely spaced axial planar fractures. (c) Steeply dipping schistosity across subhorizontal bedding of Schoongezigt pelite and psammite, (d) directly below the unconformity and (e) separated by a tectonic shear zone from the subhorizontal TMG. (f) Typical TMG quartzite, (g) conglomerate, sometimes (h) in bedding parallel shear zones, along the Kango–TMG contact at the northern margin of the Kango Complex.

error of the dated felsic dykes intruding the lower sections of the Kango Caves Group (ca. 1084 ± 5 Ma; Fig. 22). They also link closely to detrital zircon dates in the Kansa Group (ca. 1030–1080 Ma; Barnett et al. 1996; Naidoo et al. 2013). By contrast, intrusion of the ca. 512 Ma old mafic dykes were likely linked to uplift following local Pan-African deformation, often referred to as the Saldanian orogeny (e.g. Scheepers and Armstrong 2002; Gresse et al. 2009), linked along the western margin of South Africa to the East Brazilian orogens in South America (de Wit et al. 2008), and which may thus be responsible for the allochthonous and molasse deposition of the Kansa Group.

Geo-rates – ‘More Gaps Than Records’

A 10–15 km thick stratigraphic thickness covering this 700 m.y. time period reveals an average thickness of deposition between 1 and 2 m/m.y., and thus a rate of some 1–2 mm/ka, nearly 30–40 times less than the accumulation rates of limestone under the Bahamas (4–6 cm/ka; Newell 1967; Ager 1992) and 10 times less than modern sediment preservation rates on the floor of the Indian Ocean (Fig. 35). Given the thickness of many carbonate turbidites and diamictite units in the studied area, this seems extraordinarily low. While many identified unconformities and disconformities across bedding planes represent significant time gaps, more time must therefore be missing across the Kango stratigraphy due to non-deposition and erosion.



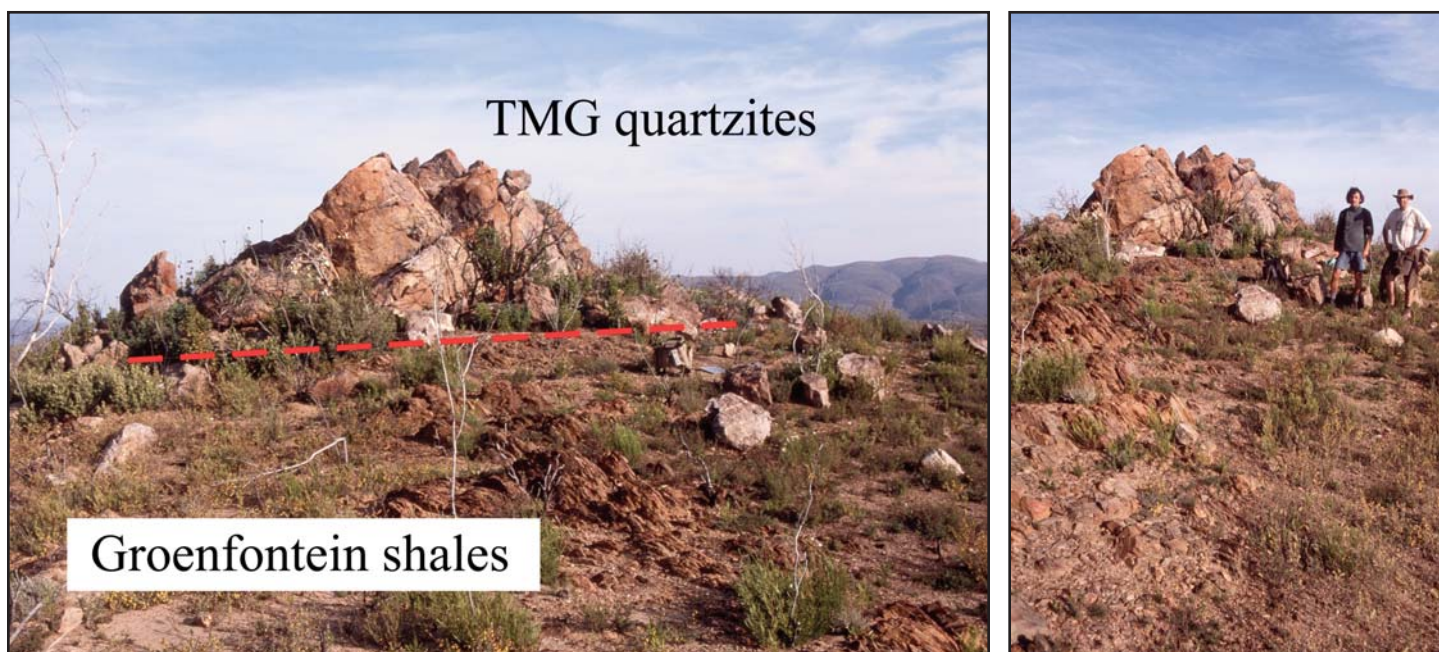


Figure 29. Subhorizontal contact between the Groenfontein Formation turbidites and TMG quartzite, cut by subvertical cleavage and joints, respectively (Section 12, Map 1); for scale students Jacek Stankiewicz (left) and John Decker (right) who first discovered these outcrops in 2004.

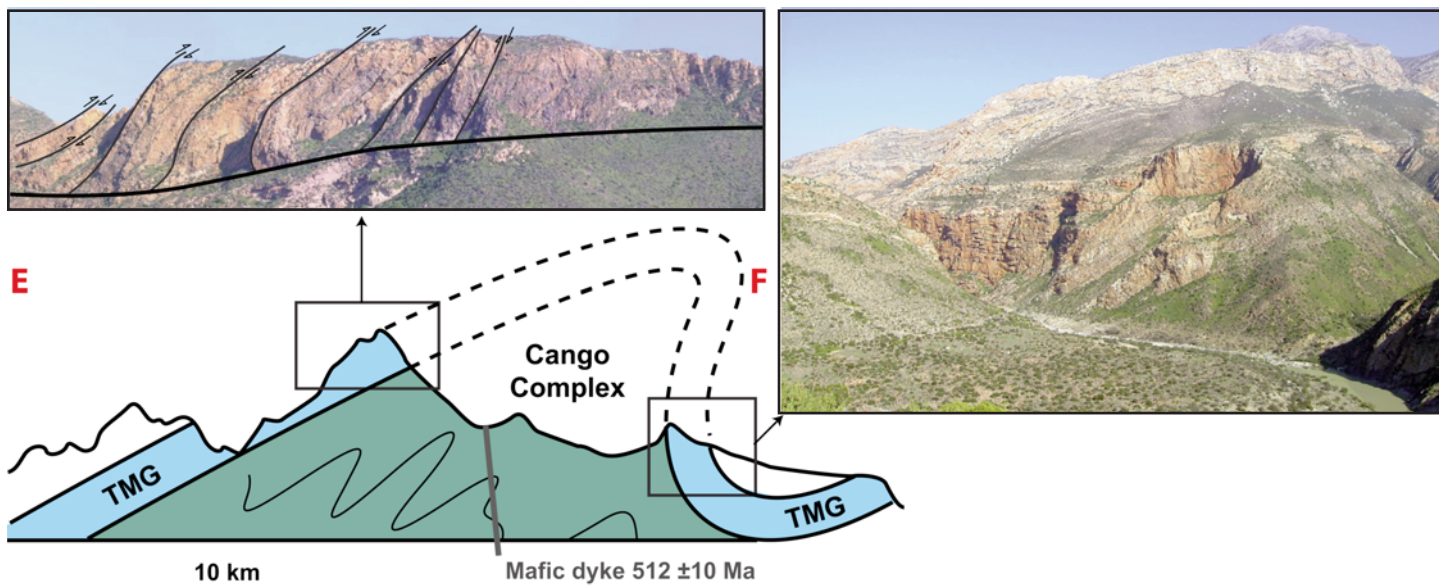


Figure 30. Schematic section across the western Kango region (Fig. 2b for location), showing a (pre-fold) accretionary thrust zone that tectonically separates TMG quartzite from Groenfontein turbidites (top left); and along an overturned section of the TMG, well-exposed along the Gamka River in the Hell (top right). Frequent conglomerate sections of the TMG preserve unconformable contacts. The dolerite dyke dated at 512 Ma links to a series of intrusive gabbro bodies in this area of the Kango Complex (Haas, 1998).

The Kango Complex represents an inescapable example of long gaps with only occasional records of sedimentation (cf. Ager 1992). It needs much created micro-stratigraphy nit-picking, linked to new geochronology techniques, to quantify these hiatuses and how they represent regional erosion processes linked to the Namaquan and Pan-African mobile belt orogens and the Kalahari epeirogeny (Dewey et al. 2006; de Wit 2007).

Since its present stalagmites date back at least 200 ka, Ager's famous idealized diagram of the condensed sequences preserved in solution hollows of Jurassic limestone (Fig. 32; Ager 1992) also fits the Kango Caves and their linked subsurface river systems well. In this case, condensed sequences within the caves may link back more than 300 Ma to the Carboniferous (Fig. 33).



Figure 31. Topography across the Cango Valley with relatively well-preserved open paleo-river sections flanking the Swartberg Mountains and eroding at ca. 0.5 to 1.5 m/m.y. over the last 5 m.y. (see below). The 1000 m asl topography in foreground (left) is covered by rounded quartzite boulders, in places with eroded impact textures (right), confirming their likely fossil link to Cretaceous paleo-river sections preserved at this high elevation.

TECTONO-STRATIGRAPHIC LINKS – LOCAL TO GLOBAL

From Kango to Table Mountain – Orogeny and Epelogeny

While there are no granite plutons exposed across the Kango region, U–Pb zircon dates from some granite boulders of the Kansa Group are ca. 518 ± 9 Ma (Barnett et al. 1997). Granite boulders from the base of the Sardinia Bay Formation in the Eastern Cape (Gamtoos Complex) also have a Cambrian age with dates at ca. 530 ± 5 Ma (Miller et al. 2016; Fig. 2b). Both are similar to the U–Pb zircon dates obtained from the Neoproterozoic–Lower Paleozoic granite intrusions of the Western Cape at 560–500 Ma (Gresse et al. 2009), and in the southern Cape (543 Ma, flanking George and Victoria Bay; Scheepers and Armstrong 2002). Therefore, the Cape Granite Suite is most likely to have been a source for the sediment (Fig. 27).

Specifically, the granite of Table Mountain in Cape Town, dated at ca. 540 Ma (U–Pb zircon date; Scheepers and Armstrong 2002), unconformably underlies the baseline of TMG quartzite (Figs. 36 and 37). Based on U–Pb dated detrital zircons, this unconformity is younger here than ca. 520 Ma (Armstrong et al. 1998); and perhaps younger than 504 Ma based on the other U–Pb detrital zircon dates from TMG in the Swartberg Mountains found directly above the Kango sequences (Fig. 33).

Final emplacement of the Table Mountain granite took place from ca. 15–18 km (5 kbar) at 750°C, intruding the sub-vertical Malmesbury greywackes some 10–20 km below surface (Armstrong et al. 1998; Villaros et al. 2009; Harris and Vogeli 2010). Thus, this granite must have been uplifted and eroded by at least 15 km within 17–20 m.y. Along the seashore, the intruded Malmesbury Group is dated with detrital zircons at about 560 Ma, which is broadly similar to the greywackes of the Groenfontein Formation (the Geogamma Group, < 620 Ma; Fig. 37).

While there are no Ar/Ar dates from rocks or minerals across the Kango Complex, such dates from the Cape Granite and its micas, calculated between 1996–2004 by Derek York and his colleagues in Canada (University of Toronto), provide a more detailed history of the cooling, multiple uplift, and erosion rates with relevance to the Kango Complex (Fig. 36).

The first dates at ca. 537 ± 0.3 Ma (MSWD of 0.79) are interpreted as the primary age of cooling of the samples through the muscovite and biotite closure temperatures. The very close agreement of ages from both minerals implies rapid cooling of the sample between their respective closure temperatures. These ages compare well with the U–Pb zircon date of ca. 540 ± 4 Ma obtained from the same outcrop (Armstrong et al. 1998) and reveal onset of cooling (uplift) within less than 3 m.y. and erosion of > 15 km within 20 m.y., reaching a relatively low apparent temperature of 440°C, well below the crystallization temperature of the Cape Granite and about 50–100°C below the closure temperature of quartz–feldspar (Harris and Vogeli 2010).

The second dates at ca. 354.1 ± 0.3 Ma (MSWD of 0.84) apparently represent a reheating episode, sufficient to completely reset the K–feldspar, to affect over 20% of the biotite's K–Ar budget, while affecting only 1.3% of the muscovite K–Ar budget, in agreement with the sequence of closure temperatures from highest (muscovite) through biotite to lowest (K–feldspar). The weighted mean age of this overprint is dominated by a precise high-temperature isochron date of the K–feldspar (Fig. 36). We interpret this age as a resetting of the Table Mountain granite/Malmesbury greywacke contact, and by inference the Kango Complex, during Carboniferous glaciation of the Dwyka Ice Age, which likely was covered by an up to 3–5 km thick Antarctic-like ice dome at 350 Ma and that had completely melted by ca. 300 Ma (e.g. Schulz et al. 2018). Thereafter, little is known about the subsequent erosion rates across Table Mountain, which today are less than 20 m/m.y. (Erlanger et al. 2012).

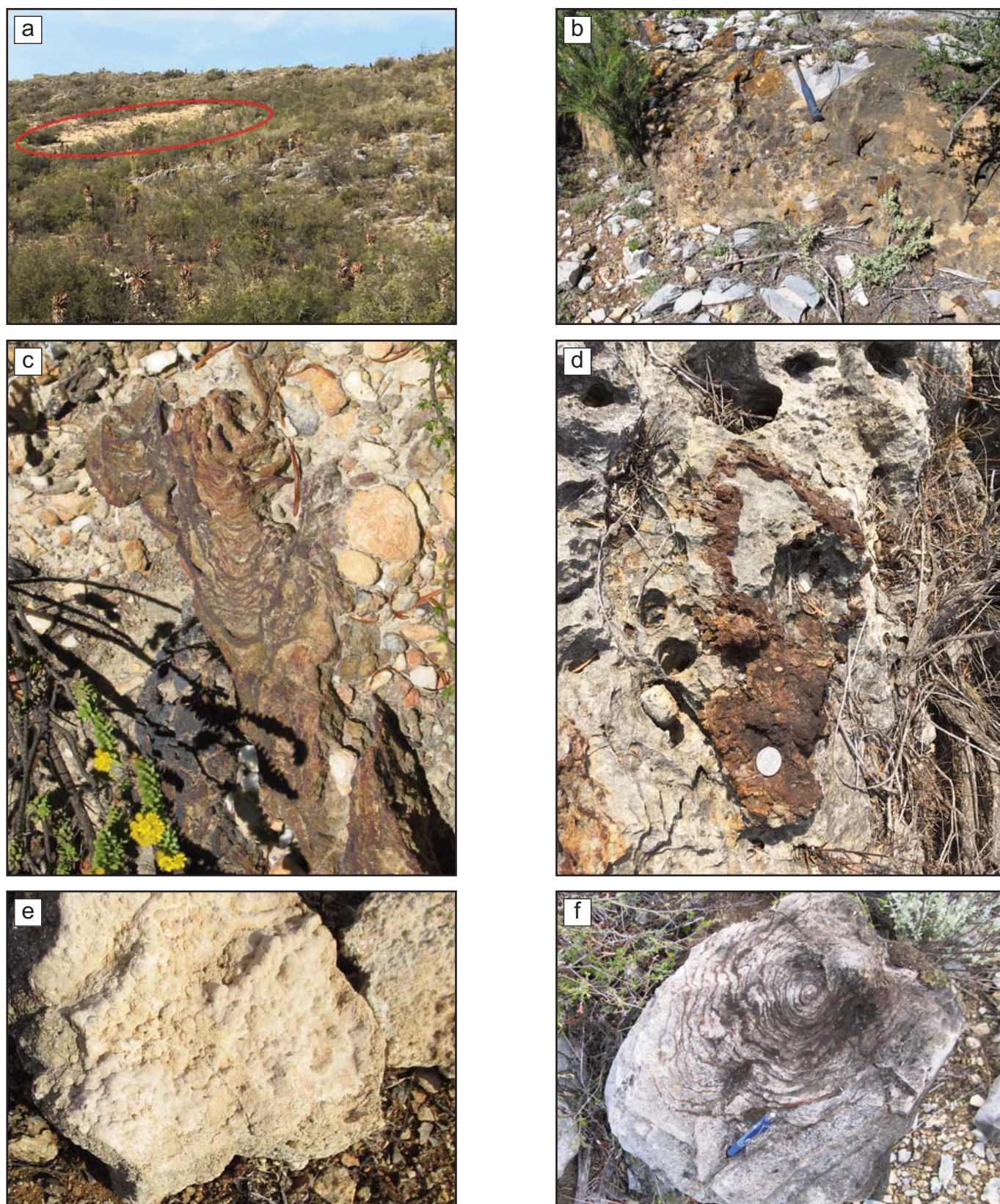


Figure 32. (a) Circular section of a 150 m wide paleo-cave (red ellipse) filled with yellow sand and conglomerate within the upper section of the Kombuis Formation (grey outcrops). (b) Cave-filled sandstone with clasts overlain by carbonate fragments (blue-grey) derived locally from the Kombuis carbonate rocks. (c) Iron precipitate (brown) covering the Cave sandstone and conglomerate. (d) Iron precipitate covering carbonate flanking the paleo-cave contact. (e) Carbonate precipitates (pale yellow) and (f) paleo-stalagmite(?) section (grey) flanking the contact with the Kombuis carbonate rocks.

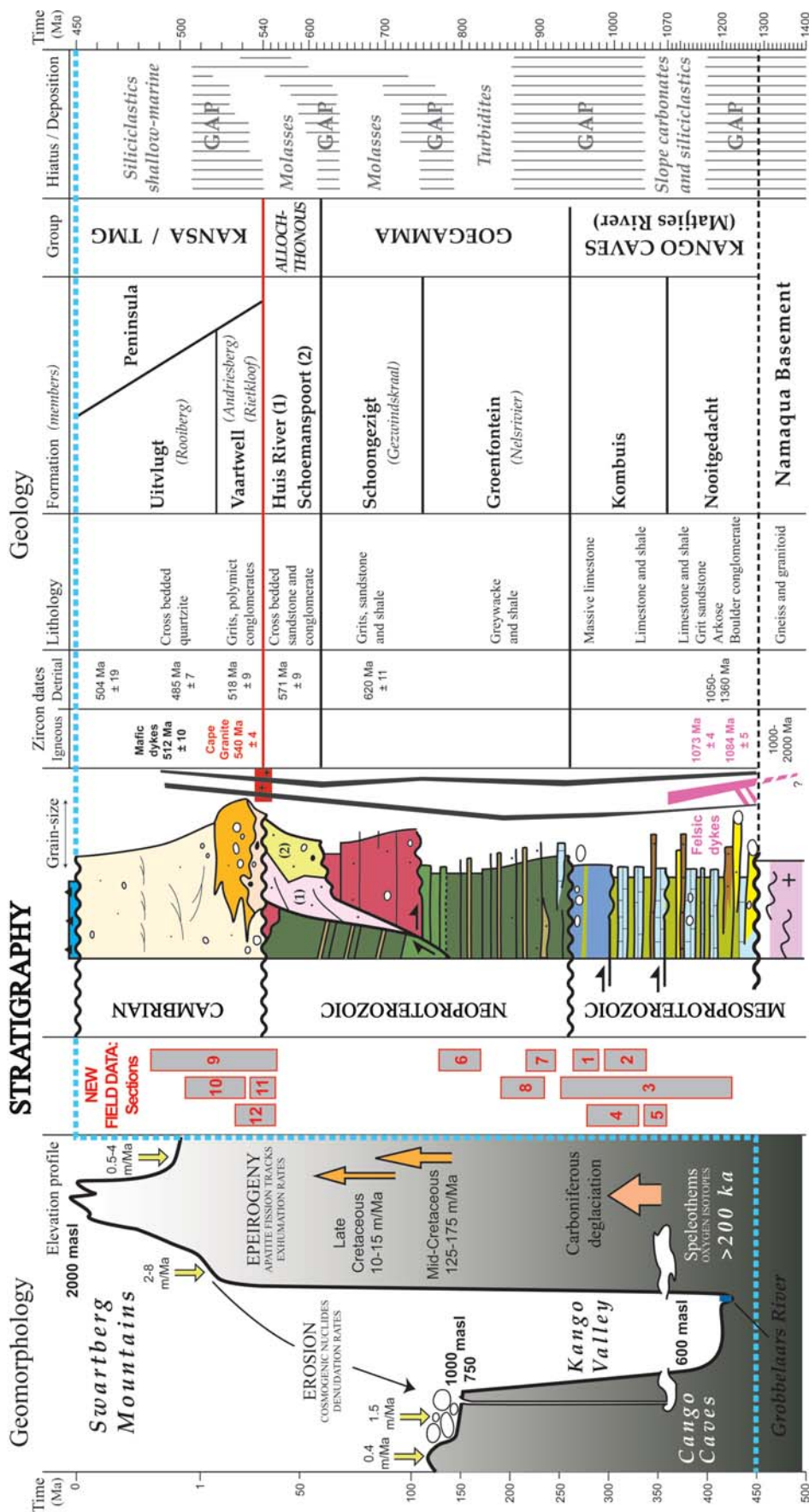


Figure 33. Revised stratigraphy of the Kango geology highlighting missing time gaps (hiatuses) linked to erosion/non-deposition events between 1300 and 450 Ma, based on U–Pb zircon data (right); and its surface geomorphology based on various isotope analyses and thermochronology (left). The stratigraphic gaps are likely of greater thickness than shown here due to poorly quantified data but based on a present average thickness of 10 km, sedimentation rates were extremely low (1.4 m/m.y.). Note that there is a poorly quantified stratigraphic overlap between the Upper Kango (Kansa Group) and TMG sequences. The geomorphology gaps are linked to unquantified erosion rates during deglaciation (twice, at 450 and 300 Ma; Linol and de Wit 2016) followed by high Cretaceous erosion rates of ca. 100–175 m/m.y. based on fission track analyses from boreholes through TMG/Karoo/Namaqua basement (Tinker et al. 2008; Brown et al. 2014), which decreased by the mid-Cenozoic to relatively low rates (< 10 m/m.y.), based on cosmogenic nuclides studies (Decker et al. 2011; Scharf et al. 2013; Kounov et al. 2015) and (U–Th)/He surface dating (Stanley et al. 2013), and in line with general low erosion rates across southern Africa today (de Wit 2007; Flowers and Schoene 2010; Decker et al. 2013; Evans 2015). Present subsurface erosion rates are also low, based on isotope analyses of stalagmites preserved in the Kango Caves (de Wit et al. unpublished).

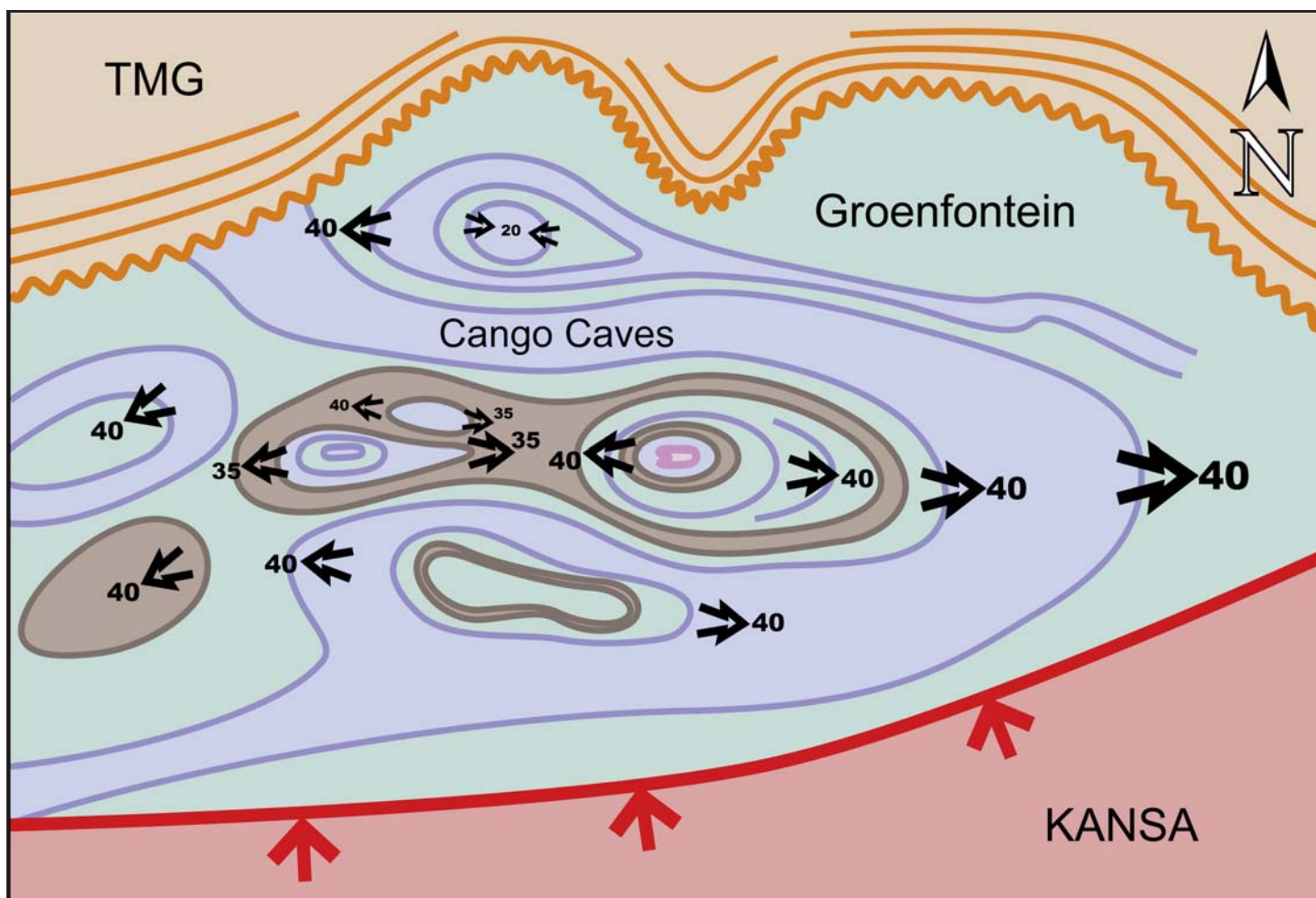


Figure 34. Simplified pre-Kansa/TMG restoration in the central part of the study area (by 50% at right angle across the cleavage/schistosity and along the fold closures) reveals a number of 8–12 km wide, 20–40° dipping domes and basins across Namaquan/Grenvillian basement. These sequences were covered by molasse-like sandstones and conglomerates of the Kansa Group and the overlapping conglomerates and quartzites of the TMG, deposited during end-Pan African times (Fig. 33).

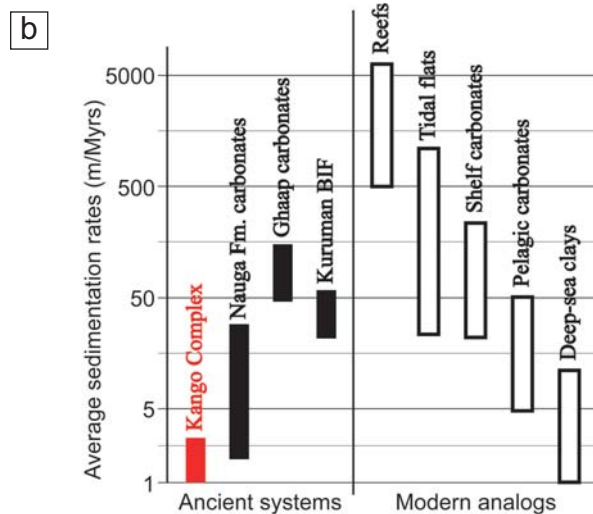


Figure 35. (a) Typical contact between parallel-bedded mudstone and feldspathic grit across the Kango Complex (Section 2). At present, there are no geochronological data that can quantify non-depositional/erosion breaks ("missing time") across these surfaces, which likely represent significant pauses in sedimentation and erosion, given the more than 700 m.y. period recorded across the total 10 km thick stratigraphy. (b) Average deposition rates across variable sedimentary systems; the average accumulation rate of the Kango system is about 1.5 m/m.y. (highlighted in red), comparable only to the lowest sedimentation rates across modern deep oceans (modified from Altermann and Nelson 1998).



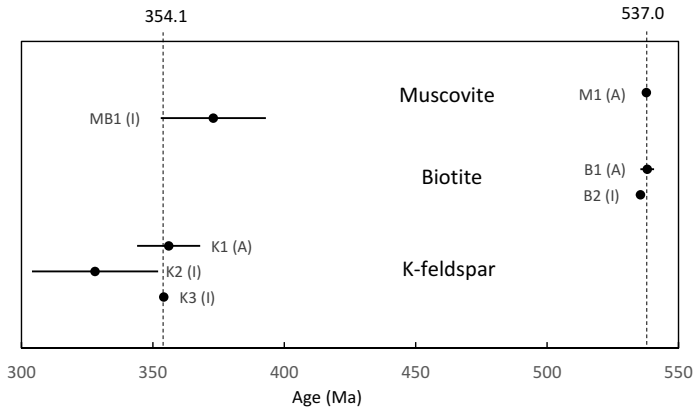


Figure 36. Detailed $^{40}\text{Ar}/^{39}\text{Ar}$ step heating results on single grains of biotite (11 steps), muscovite (16 steps) and K-feldspar (59 steps) from a whole-rock sample of the same Cape Granite reveal uplift/erosion during two distinct episodes.

Across West Namaqualand

Farther north, many U–Pb zircon dates of the Namaqua Natal Mobile Belt reveal igneous and metamorphic ages near the end of the Mesoproterozoic, between ca. 1230 and 1025 Ma (Friese et al. 1996; Thomas et al. 1996; Barnett et al. 1997; McCourt et al. 2006; Cornell et al. 2006; Minnaar et al. 2017; Moen and Cornell 2017; Macey et al. 2018).

The closest regional stratigraphic equivalents of the Kango sequences are rocks exposed in West Namaqua and within the Saldania Belt near Cape Town (Fig. 38). The Namaquan basement is dated between about 2.0 and 1.0 Ga, including some late tectonic intrusions dated at ca. 1030–1100 Ma, and surrounding feldspathic quartzites (the Bitterfontein Subgroup; Joubert 1986), which are similar to those described and dated in this study of the Kango Complex. To compare with the Goegamma and Kansa groups the tectono-stratigraphy of the other time equivalent, Precambrian–Lower Paleozoic sequences across the Saldania Belt remains poorly resolved. This is due to limited field mapping, which prevents precise correlations for example with the Malmesbury Group (Fölling and Frimmel 2002; Frimmel 2018; Zimmermann 2018).

From Gondwana to Rodinia

Large uncertainties exist in the global paleogeographic reconstructions between about 1300 and 500 Ma, during deposition of the Kango sequences (e.g. Cawood et al. 2016; Merdith et al. 2017). However, possible connections during the Mesoproterozoic Namaquan–Grenvillian orogenies, and again during the Late Paleozoic Variscan–Gondwanan orogenies, suggest similar tectonic basin evolution in southern Africa and in northern America (Fig. 39).

The oldest sequences of limestone and feldspar-rich sandstone of the Kango Complex (including the Cango Caves limestone) were intruded by ca. 1070–1080 Ma old felsic dykes (Fig. 33). These earliest clastic sedimentary rocks are linked to rapid uplift and erosion of relatively low-pressure Namaqua granites and charnockites during their extensional unroofing flanking the Grenvillian Mountains system. While such basement rocks are not exposed in the Cango region, relatively abundant granite and pegmatite pebbles preserved in the lowest sequences suggest a close connection to a flat Namaquan basement that hosted shallow marine platforms which were the sources of carbonate slope conglomerates, breccias and turbidites linked to sea-level changes and extensional tectonics along a continental margin perhaps analogous to that proposed for the Paleozoic Cow Head–Fleur de Lys sequences in Newfoundland.

The Kango Caves Group limestone is unconformably overlain by the Goegamma Group comprising sandy turbidites and laminated siltstones deposited between 900 and 700 Ma and linked to molasse-like sandstones and conglomerates in front of Pan-African mountain belts by ca. 620 Ma (Fig. 39). These sequences were all unconformably overlain between 530 and 500 Ma by shallow marine sandstones of the Kansa and Table Mountain groups, with conglomerates that contain granite boulders post-dating intrusion and erosion of granite down to sea level across the Western Cape at ca. 520 Ma, ahead of the onset of glaciation across southern Gondwana during the Early Paleozoic.

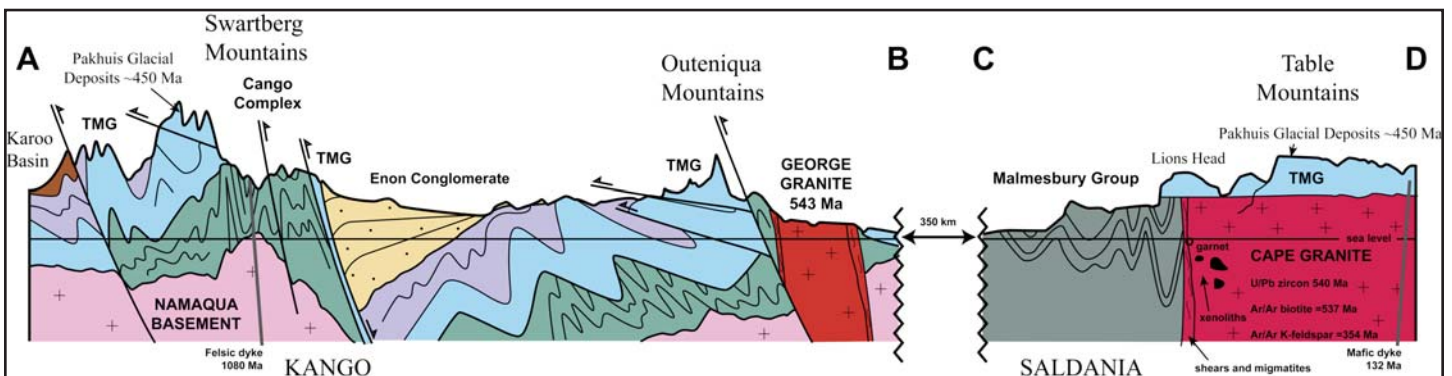


Figure 37. Schematic cross-sections of the Swartberg and Table mountains, highlighting chronostratigraphic differences between the Table Mountain Group (TMG) and its underlying sequences (Fig. 2a for location). In both areas the youngest dated detrital zircon grains from quartzites of the TMG that unconformably overlie granites and metasedimentary rocks range between 520 and 504 Ma, revealing a stratigraphic time gap of 20 to 100 m.y. between the Goegamma–Malmesbury and the Table Mountain groups. However, the precise ages of these sequences are poorly constrained: between 950 and 610 Ma (for the Malmesbury – Scheepers 1995; Harris and Vogeli 2010); and between 1000 and 570 Ma (for the Goegamma – Naidoo et al. 2013), respectively. No Archean zircon grains derived from the Kaapvaal Craton have been reported yet in the Kango and Saldania sequences as they have across the TMG (Scheepers and Armstrong 2002; Naidoo et al. 2013). There are still many outstanding data needed to test these possible links, including along the south coast near George (e.g. Gresse et al. 2009; Kirsters 2016; Kirsters and Belcher 2018).



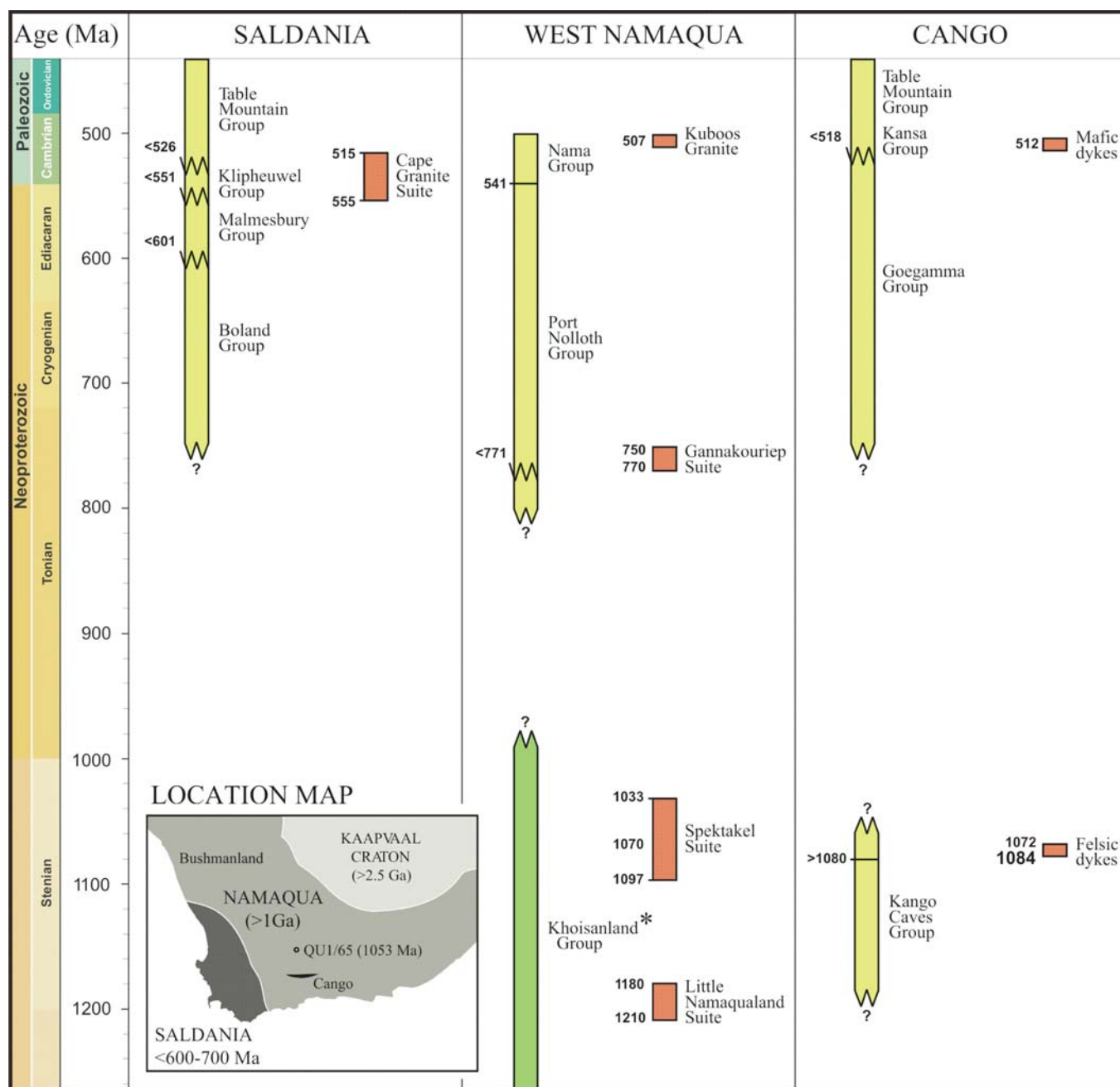


Figure 38. Stratigraphic table comparing sedimentary (yellow), high-grade low-pressure metamorphic (green), and intrusive (red) rock records from Namaqualand and Swartland with the Kango Complex, compiled from Joubert (1986), Barnett et al. (1997), Scheepers and Armstrong (2002), Eglington and Armstrong (2003), Frimmel et al. (2013), Frimmel (2018), and this study (right); see inset for location. Most maximum ages of sedimentation are uncertain due to limited field constraints, but most likely the Kango Caves Group correlates with similar quartzite–schist sequences (e.g. the Bitterfontein SubGroup) of the Khoisanland Group*.

* renamed after the colonial Bushmanland.

The Kango rocks thus trace the orogenic histories of Grenville and Appalachia across Canada to epeirogeny across South Africa, preserving a globally unique stratigraphic section that encapsulates this long history of changes from Rodinia to Africa.

CONCLUSION

The new geological map and detailed descriptions of sedimentary and deformational structures of a central-eastern section

of the Kango region of southern South Africa improve our understanding of the regional stratigraphy. Together with new U–Pb zircon dates of dykes and the existing geochronology, geophysics, geomorphology, cosmogenic nuclides and thermochronology, and global geodynamic models, this review provides a solid foundation for further field investigations.

The Kango Complex preserves a ca. 8–10 km lithostratigraphic record with a significant number of disconformities between 1200 and 500 Ma, with an average preservation rate



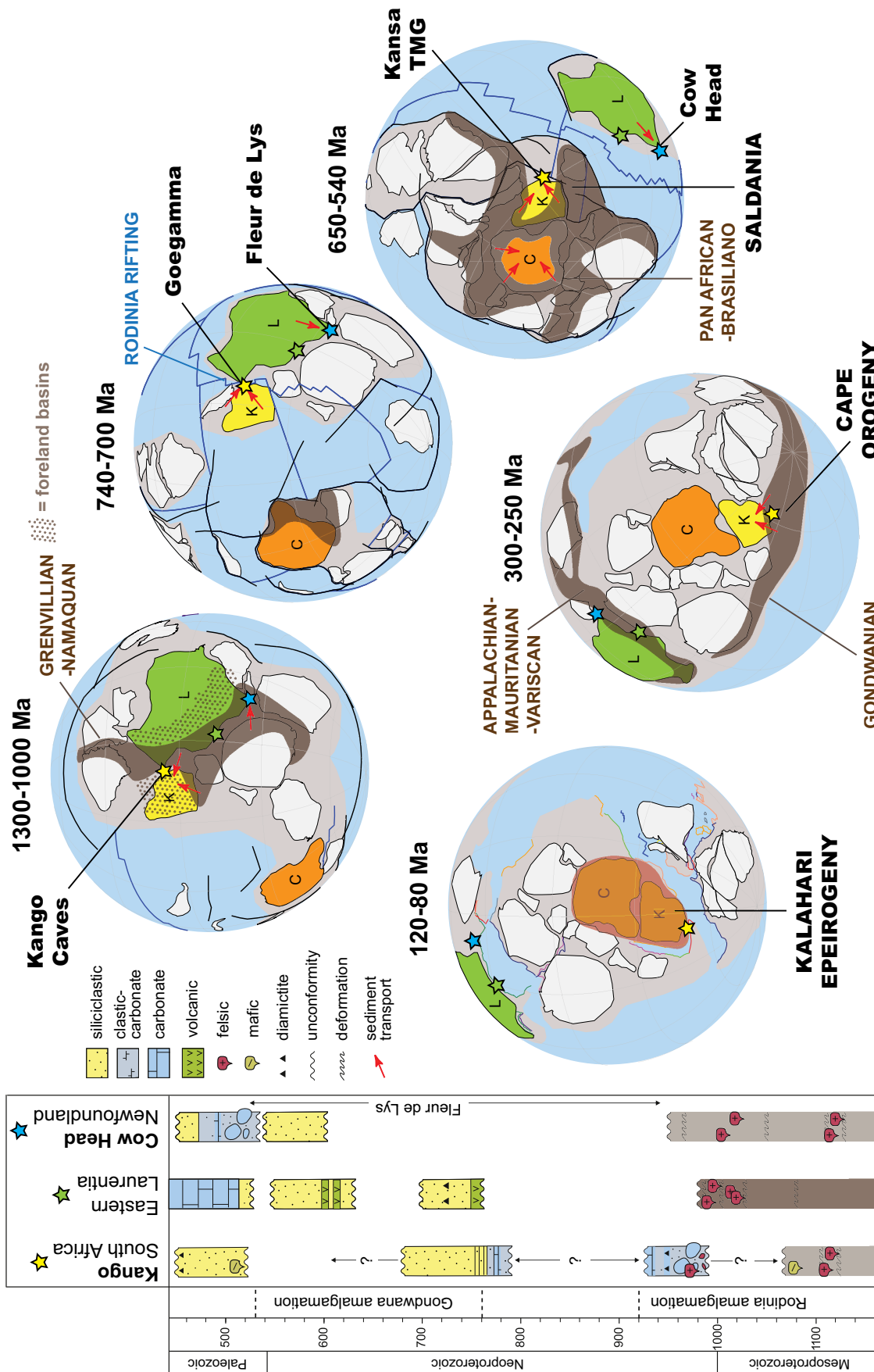


Figure 39. Simplified history between 1300 and 80 Ma of sedimentation and erosion preserved across the Kango sequences linked to global evolution of Rodinia to Africa via Pangea and Gondwana, highlighting rapid erosion of Grenvillian-linked Namaquan foreland and onset of deposition of carbonate conglomerates similar to the famous Lower Paleozoic Cow Head deposits of Newfoundland some 600 m.y. later (Supercontinent reconstruction in Gplates is modified from Meredith et al. 2017); C= Congo Shield; K= Kalahari Shield; L= Laurentian Shield.

of about 1.5 m/m.y., and thereafter overlapping in time with the Table Mountain Group (TMG) to at least 486 Ma. Between 450 and 350 Ma, these Kango and TMG sequences vertically subsided variably by up to 4 km below Antarctic-size ice sheets that yielded Pakhuis and Dwyka glacial deposits across southern Gondwana. After deglaciation by 300 Ma, and the Cape orogeny (252 Ma), the Kango Complex was uplifted vertically and eroded by ca. 3–5 km at rates between 100 and 200 m/m.y. during the Jurassic–Early Cretaceous, decreasing to less than 10 m/m.y. today. These variable rates left a complex paleosurface and subsurface geomorphology across the Congo region, including different plateau elevations, valleys, canyons and caves.

Based on the low rates of sedimentation and erosion, the Kango Complex is a prime example of a long stratigraphic record with, apparently, more “Gaps than Records” (e.g. Åger 1973, 1992), but based on little age data. This recording deserves more testing through more innovative geo-timing (e.g. Bowring et al. 2006). The varied landscapes across the Congo region offer an excellent opportunity for new transdisciplinary sciences to try and close these gaps.

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Andrew Hynes visited the Congo with Maarten de Wit in 2002 and provided inspirational suggestions, including potential links with Grenvillian and Appalachian sequences in Canada. It has taken nearly 15 years to document this, in part because we all know his expectations. Even earlier, Arthur Fuller (AF) first drove Maarten through the Congo following his arrival at University of Cape Town (UCT), making sure that he would follow up Arthur's field sedimentology there for more than 20 years, but which he never published; and thanks to Lester King for similar inspirations about the Congo geomorphology during a Gondwana workshop in 1979 at the Bernard Price Institute at Wits University. This would also not have happened without the visions of Louis Nicolaysen (LN). AF and LN were remarkable geologists, if somewhat elusive persons who completed their PhDs in Princeton University where AF got to know Albert Einstein, and where LN designed how best to display Rb–Sr isotope data. Some of the early Kango whole-rock samples were dated by this method in the 1980s by Hugh Allsopp, and subsequently by U–Pb, following a decade of multi-disciplinary co-operation among earth scientists from six South African universities, and its Geological Survey, during the Inter Union Commission of Geodynamics of the IUGS and IUGG (Nicolaysen 1983).

By 1995, Richard Armstrong dated the first zircon grains collected by honours student Wayne Barnett. Then during a following decade, Derek York completed the Table Mountain Ar–Ar analyses by 2006 following his sabbatical year in Cape Town in 1996. In 2004, the new U–Pb zircon dates of felsic dykes were completed by Kerstin Drost. Maarten owes them all a deep apology for letting this all remain in his proverbial drawers for so long.

We thank all undergraduate students of UCT (1996–2014) and Nelson Mandela University (2014–present) for their hard mapping during field classes, and all Masters/PhD researchers that acted as field guides during these annual weeks to get away from their own routines. There are too many students (> 100) to mention individually, but they will remember their slogs in rain, snow and sunshine; and during their report writing. We also thank the managers of the Congo Caves and De Hoek Resort for putting up with these rowdy students for all those years.

Maarten, who left us during the finalization of this work, has inspired many young South Africans with the examples of the Kango. We would like to thank him for sharing his passion for field mapping and his enthusiasm in taking this transdisciplinary research forward.

This is AEON contribution 197 and Iphakade publication number 247.

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For access to the de Wit et al. (2020) Supplementary Material: Appendix: U–Pb dated zircon grains from selected felsic dykes of the lower Kango Complex (Sections 5 and 6, Map 1), and U–Pb data tables and plots for samples K08-01, -02, and -03, please visit the GAC's open source GC Data Repository for the Andrew Hynes Series: Tectonic Processes at: <https://gac.ca/gc-data-repository/>.





Andrew investigating the geology of Greece during his PhD studies and much later in a celebratory trip with his supervisor Alan Smith.