U-Pb zircon age for a tuff in the Campbell Group, Griqualand West Sequence, South Africa: Implications for Early Proterozoic rock accumulation rates

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ABSTRACT

An ion-microprobe U-Pb age of 2552 ±11 Ma has been obtained on zircon separated from a regional banded-tuff horizon in the Nauga Formation (Beukes, 1980b) (upper Campbell Group, Griqualand West Sequence, South Africa). This age permits time constraints to be placed on lithologically correlated units within the adjacent Transvaal Sequence and correlations to be made with the further removed Hamersley Group in Australia. Calculated rock accumulation rates of 2 to 4 m/m.y. for these strata of mainly shale and banded iron formation suggest that sedimentation rates were significantly slower in the late Archean–Early Proterozoic than is generally assumed.

INTRODUCTION

The late Archean–Early Proterozoic Campbell Group and Malmani Subgroup (South African Committee for Stratigraphy, 1980) of South Africa contain one of the oldest known carbonate-platform sequences and are correlated on the basis of lithology and geochronology with similar rocks of the Hamersley basin in Australia (e.g., Trendall et al., 1990). Commonly, such correlations are controversial because of the lack of precise depositional ages for stratigraphically well documented samples. However, the correlation of the Asbestos Hills Iron Formation (Griqualand West Sequence) with the Penge Iron Formation (Transvaal Sequence) is widely accepted (e.g., Beukes, 1983) (Figs. 1 and 2). The zircon U-Pb age measured on a tuff horizon within the Nauga Formation provides a maximum age limit for the overlying Asbestos Hills Iron Formation, the focal point of the regional correlations.

GEOLOGIC AND GEOCHRONOLOGICAL SETTING

The late Archean–Early Proterozoic Griqualand West and Transvaal Sequences of South Africa are preserved in the Ghaap and Chuniespoort basins, respectively (Fig. 1). The maximum age of the Transvaal Sequence is constrained by U-Pb ages of 2714 ±8 and 2709 ±4 Ma measured on zircon from mafic and felsic volcanic rocks from the unconformably underlying Ventersdorp Supergroup (Armstrong et al., 1991). The regional correlations and sedimentary facies relations between these basins and the localities of the samples discussed in the text are shown in Figure 2. The Asbestos Hills Iron Formation (South African Committee for Stratigraphy, 1980) incorporates both the Kuruman and Griquatown Iron Formations of Beukes (1980a).

Stromatolitic limestones from the Schmidtsdrif Formation yield a whole-rock Pb-Pb age of 2557 ±49 Ma (Jahn et al., 1990), which was interpreted as the time of dolomitization of the stromatolitic carbonates on the grounds that there is no evidence for metamorphic recrystallization. The samples dated by Jahn et al. (1990) can be correlated with the Ulco Member of South African Committee for Stratigraphy (1980) or the Reivilo Formation of Beukes (1980b), which is the lowest part of the ~1700-m-thick Campbell Group and thus, unlike the Nauga Formation, is stratigraphically far below the transition zone between the carbonate and the Asbestos Hills Banded Iron Formation. Diagenetic and hydrothermal alteration effects in the Campbell Group were noted by Beukes et al. (1990) and Bertrand-Sarfati and Eriksson (1977). The age recorded by Jahn et al. (1990) is therefore likely to be a minimum estimate for the deposition of these stromatolitic carbonates.

Trendall et al. (1990) reported an ion-microprobe U-Pb age of 2432 ±31 Ma for zircon from the Kuruman Iron Formation; however, the data on which this age is based and the precise locality of the sample site have not been published. According to N. J. Beukes (1993, personal commun.), who collected the sample, the zircon was extracted from a tuff layer located at the base of the Griquatown Iron Formation just above the top of the Ouplaas Member of the Kuruman Iron Formation (see Beukes, 1980a).

NAUGA FORMATION SAMPLE LOCALITY AND PETROGRAPHY

Beukes (1980a) described five tuff layers in the Nauga Formation; the uppermost Tuff 1 (90 m below the Naute Shale Formation in the type locality) was sampled for zircon analysis. This layered tuff horizon, about 10 cm thick, is intercalated within a relatively undisturbed section at the top of the Campbell Group about 60 m below the Naute Shale Formation and 150 m below the Asbestos Hills Iron Formation at the sample site (Figs. 1 and 2). It commonly appears as several graded 2–3-cm-thick lapilli to ash-fallout tuff beds, each of which is defined by a sharp base and is interpreted to represent one eruptive pulse within some larger cycle. Microscopically, 90% of the tuff unit is composed of angular to very angular single-crystal grains of feldspar and (rarely) quartz and abundant lapilli-sized, (rarely) shard-shaped recrystallized glass fragments in a chloritized ash matrix. The remaining 10% is recrystallized feldspar and quartz fragments with fluidal textures. An idiomorphic zircon was found in one thin section.

In oblique reflected light, the grains of zircon are uniformly clear and range from pale pink to dark pink. The grain size is consistently about 100 μm. The zircon habit is equant-shaped euhedral grains, commonly with broken edges. Some of these fragments have abraded and pitted surfaces that could be attributed to either a short-lived eolian transport or diagenesis. In transmitted light, the grains of zircon showed no internal structures, apart from variably well to poorly developed magmatic zoning. No inclusions were observed.

RESULTS

Fifteen of the sixteen grains analyzed have, within error, equal radiogenic ^{207}Pb/^{206}Pb ratios, giving a weighted mean age of 2552 ±11 Ma (Table 1; Fig. 3). The data for

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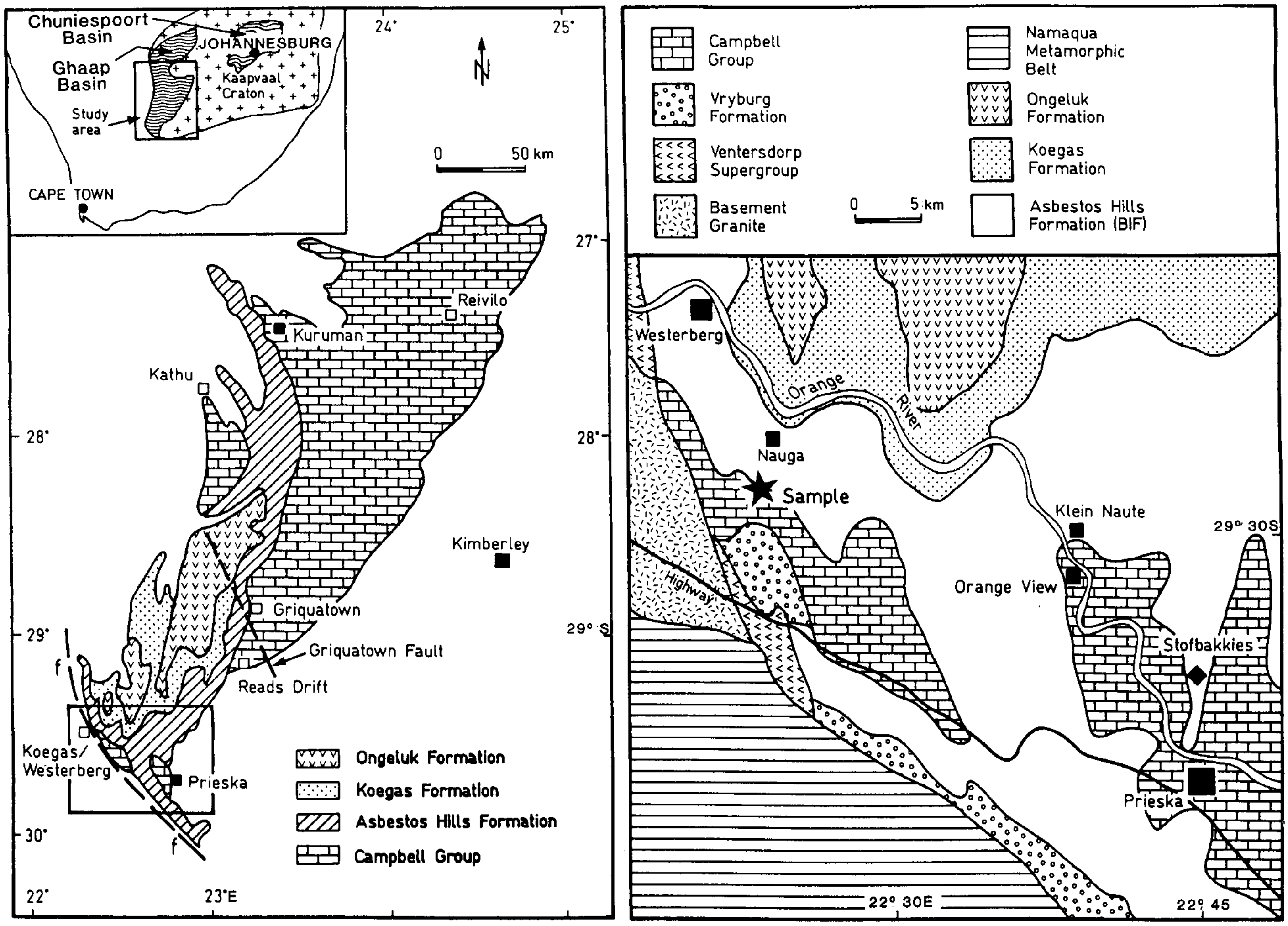

Figure 1. General and progressively more detailed geologic maps of region of Nauga sample (star in map at right). BIF = banded iron formation; f = fault.

14 of these grains plot in a tight group and are virtually concordant. Grain 4 is 15% discordant and has a high common-Pb component but the same radiogenic $^{207}Pb/^{206}Pb$ ratio. The excellent consistency in $^{207}Pb/^{206}Pb$ ages and the euhedral morphology of the zircon are interpreted to denote the crystallization of a magmatic zircon population at about 2550 Ma. Grain 11 is anomalous with a younger concordant age of 1876 Ma, a significantly higher U content of 189 ppm, and a euhedral prismatic morphology. We believe that this grain is a contaminant introduced during sample preparation, and so we do not consider it further here.

The U contents are uniformly low, with a mean value of 58 ppm (Table 1), whereas the Th contents are mostly high, the majority being between 500 and 800 ppm. The resulting range in Th/U ratios from 0.9 to 18.4 is extraordinarily high for zircon. The tuff horizons have subalkalic basalt to andesite compositions (Altermann, 1991), and zircon from rocks of this composition is generally not enriched in U or Th. The morphology is controlled by both rate of crystallization and the chemistry of the melt. The equant habit is favored by slower crystallization and increasing content of elements such as U and Th (Speer, 1980); however, in this case U and Th appear to be decoupled. Such consistently high Th/U has not to date been documented, and it remains to be seen whether this is a feature of igneous rock units in this region.

IMPLICATIONS OF THE PRECISE AGE OF THE CAMPBELL GROUP

Estimation of rock accumulation rates requires precise determination of dates and thicknesses for regionally recognized units and the perhaps unlikely assumption (e.g., Krapez, 1993) that the present stratigraphy reflects a continuous and undisturbed sedimentary record. It is important that rock accumulation rates be determined from profiles in comparable facies environments; in this case, they are estimated from the carbonate-platform region (Beukes, 1980a, 1980b).

Within the 2σ uncertainty limits given, the maximum age for the Schmidtsdrif Formation is 2606 Ma (Jahn et al., 1990), and the minimum age for the upper Campbell Group is 2541 Ma (this study). These ages give a minimum rate of 26 m/m.y. to deposit the estimated 1700 m of mainly carbonate strata separating the two dated horizons. Growth rates of about 400 m/m.y. are reported for Holocene stromatolites at Shark Bay, Western Australia (Chivas et al., 1990).

Arndt et al. (1991) proposed an extremely slow rock accumulation rate of about 3–4 m/m.y. for the deposition of the ~650 m of shale, banded iron formation, and carbonate between the Nallanaring Ignimbrite (top of the unconformably underlying Fortesque Group) and the Dales Gorge Member (Brockman Iron Formation). This value is in great contrast to rates of ~570 m/m.y. for the Campbell Group–Asbestos Hills Iron Formation transition zone calculated on the basis of annual varves (Klein and Beukes, 1989) and 40 m/m.y. estimated for present-day uncompacted pelagic sediments (Muller and Mangini, 1980).

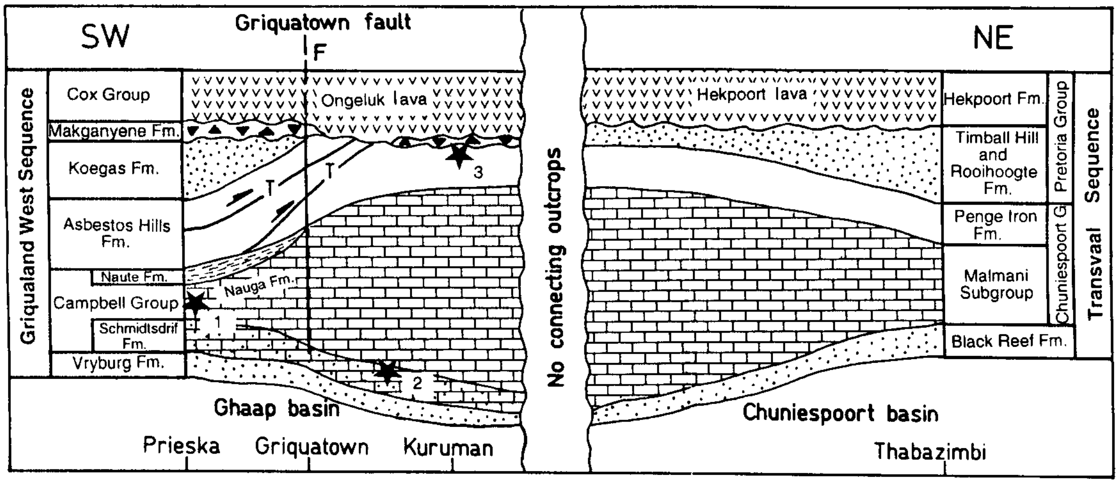

Figure 2. Regional stratigraphic setting and correlation of iron formation within Griqualand West and Transvaal Sequences along section from Prieska in southwest to Thabazimbi in northeast. Modified after Altermann and Herbig (1991). Asbestos Hills Iron Formation comprises both Kuruman and Griquatown Iron Formations of Beukes (1980a). Stars numbered 1, 2, and 3 indicate sample sites for Nauga Formation, Schmidtsdrif Formation (Jahn et al., 1990), and Griquatown Iron Formation (Trendall et al., 1990), respectively. T = thrust.

TABLE 1. ION MICROPROBE U-Th-Pb ANALYSES OF ZIRCONS FROM THE CAMPBELL GROUP, SOUTH AFRICA

									Age (Ma)			
Grain	U (ppm)	Th (ppm)	Th/U	Common ^{206}Pb (%)	^{208}Pb/^{206}Pb + (1σ)	^{206}Pb/^{238}U + (1σ)	^{207}Pb/^{235}U + (1σ)	^{207}Pb/^{206}Pb + (1σ)	^{208}Pb/^{232}Th + (1σ)	^{206}Pb/^{238}U + (1σ)	^{207}Pb/^{235}U + (1σ)	^{207}Pb/^{206}Pb + (1σ)
1	46	96	2.1	0.02	0.629 (6)	0.517 (14)	12.3 (4)	0.173 (2)	2900 (87)	2686 (58)	2630 (28)	2588 (16)
2	38	482	12.6	0.70	3.772 (30)	0.487 (13)	11.1 (4)	0.165 (3)	2742 (82)	2558 (58)	2533 (34)	2513 (34)
3	51	641	12.5	0.60	3.689 (25)	0.473 (12)	11.0 (4)	0.169 (3)	2648 (74)	2495 (54)	2526 (30)	2551 (26)
4	39	549	13.9	2.04	4.593 (41)	0.386 (10)	8.6 (4)	0.162 (5)	2426 (71)	2105 (48)	2300 (38)	2478 (49)
5	57	595	10.4	0.21	3.095 (20)	0.509 (13)	11.8 (4)	0.168 (2)	2847 (77)	2654 (56)	2590 (28)	2540 (20)
6	51	869	17.0	0.43	5.091 (35)	0.491 (13)	11.3 (4)	0.167 (3)	2776 (78)	2574 (56)	2546 (32)	2525 (31)
7	35	550	15.6	0.44	4.700 (38)	0.485 (13)	11.5 (4)	0.173 (3)	2762 (83)	2549 (58)	2568 (33)	2583 (30)
8	82	70	0.9	0.25	0.246 (3)	0.497 (12)	11.5 (3)	0.168 (2)	2693 (81)	2599 (54)	2563 (26)	2535 (16)
9	52	538	10.3	0.39	3.133 (24)	0.473 (12)	11.1 (4)	0.170 (3)	2707 (76)	2498 (55)	2533 (32)	2561 (31)
10	36	658	18.4	0.36	5.553 (41)	0.485 (13)	11.4 (4)	0.171 (3)	2765 (80)	2551 (57)	2560 (32)	2567 (30)
11	189	196	1.0	0.05	0.306 (2)	0.335 (8)	5.3 (1)	0.115 (1)	1911 (48)	1865 (38)	1870 (22)	1876 (12)
12	61	1042	17.1	0.01	5.070 (28)	0.482 (12)	11.4 (3)	0.171 (1)	2704 (71)	2537 (53)	2556 (26)	2572 (14)
13	138	182	1.3	0.15	0.390 (3)	0.463 (11)	10.8 (3)	0.168 (1)	2596 (65)	2455 (49)	2503 (24)	2542 (11)
14	32	116	3.6	0.59	1.055 (13)	0.491 (14)	11.5 (4)	0.170 (4)	2711 (89)	2574 (60)	2568 (35)	2562 (35)
15	121	1304	10.7	0.17	3.119 (14)	0.487 (12)	11.4 (3)	0.170 (1)	2675 (65)	2559 (52)	2559 (25)	2559 (14)
16	36	350	9.7	1.02	2.908 (25)	0.496 (14)	11.1 (4)	0.163 (3)	2814 (85)	2596 (59)	2533 (34)	2483 (35)

Note: The zircon grains were mounted in epoxy and sectioned by polishing. The SHRIMP I ion microprobe at the Australian National University was used to analyze areas (25 μm in diameter) on the clearest part on individual zircon grains, using techniques described in detail by Compston et al. (1984) and Williams and Claesson (1987). The Pb isotopic composition was measured directly. Pb/U and Th/U were determined by reference to analyses of a chip of standard zircon (SL13) cast into the mount. ^{206}Pb/^{238}U in the standard was assumed to be 0.0928, equivalent to an age of 572 Ma. Each analysis consisted of five scans through the species of interest, achieving a precision of 2.3% for a single determination of Pb/U. Corrections for initial Pb (given by the % common ^{206}Pb) were made by using the measured ^{204}Pb/^{206}Pb and by assuming common Pb of contemporary crustal composition (Cumming and Richards, 1975). The constants recommended by Steiger and Jaeger (1977) were used to calculate the ages. Uncertainties in U and Th concentrations are about 20%. Uncertainties quoted for all ages discussed in the text are for 95% confidence limits.

There is a gap of about 120 m.y. between the tuff layer deposited at 2552 Ma in the upper part of the Campbell Group (this study) and the tuff layer deposited at 2432 Ma in the lower part of the Griquatown Iron Formation (Trendall et al., 1990). The maximum and minimum estimates of the time gap, taking into account the 2σ uncertainties, are 162 and 78 Ma, respectively. The type section of the Nauga Formation is in the basinal-deep-shelf facies according to Beukes (1980b) or in the shallow-marine facies according to Altermann and Herbig (1991). In the type locality, the Naute Shale Formation is well developed, and the sample locality in the Tuff 1 horizon is about 150 m below the Kuruman (Asbestos Hills) Iron Formation, which is ~750 m thick. This enormous thickness has recently been attributed to thrusting (Altermann and Halbich, 1991). The Naute Shale Formation,

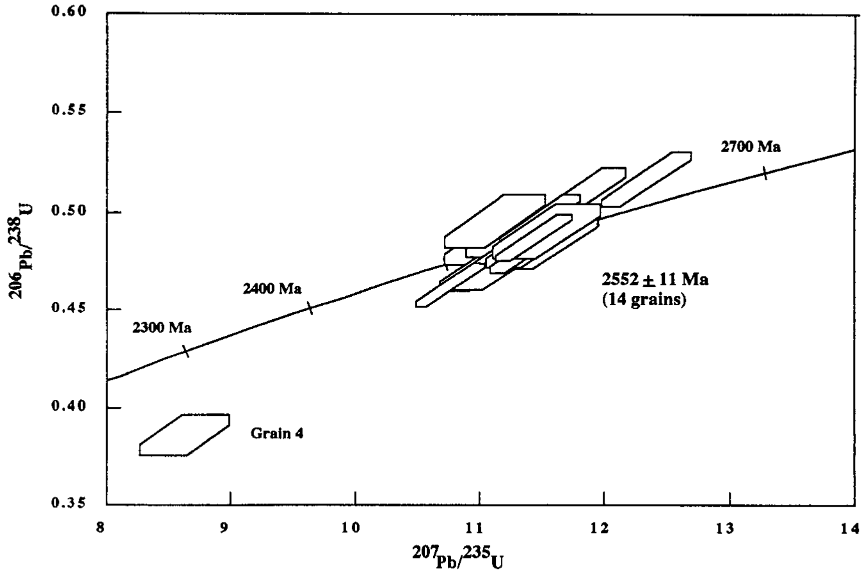

Figure 3. Conventional concordia diagram showing isotopic compositions of zircon from Nauga Formation. See text for details.

and the underlying carbonates in which the Tuff 1 horizon is located, thins dramatically toward the north, and in the platform facies, the Tuff 1 horizon is only about 20 m below the Kuruman Iron Formation. The zircon dated by Trendall et al. (1990) was from a tuff horizon at the base of the Griquatown Iron Formation about 210 m above the base of the Kuruman Iron Formation (Beukes, 1980a), in the vicinity of Kuruman (Fig. 2). The total stratigraphic distance between the two dated tuff horizons, in the platform-facies environment, is therefore about 230 m, corresponding to a rock accumulation rate of 1.4–3 m/m.y. This is comparable to the 3–4 m/m.y. estimated for the Hamersley Group (Arndt et al., 1991).

The implication of these two independent studies in the Ghaap and Hamersley Groups is that rock accumulation rates in late Archean–Early Proterozoic time may have been dramatically slower than those observed in younger, lithologically equivalent deposits. The stratigraphy in both cases is dominated by shale, banded iron formation, and, to a lesser extent, dolomite. The rock accumulation rate, calculated to be a minimum of 26 m/m.y., for the predominantly underlying dolomitic deposits appears to have been more rapid than that of the overlying shale and banded-iron-formation deposits.

The Dales Gorge Member (lowermost unit in the Brockman Iron Formation) dated at 2470 ±4 Ma (Trendall et al., 1990) is about 260 m above the Marra Mamba Iron Formation, which is stratigraphically the lowermost iron formation in the Hamersley Group (see Trendall, 1983, p. 80) and which overlies the Jeerinah Formation, dated at 2690 ±16 Ma (Arndt et al., 1991), of the Fortescue Group. The distances from the base of the Marra Mamba Iron Formation to the base and the top of the Dales Gorge Member are about 600 and 450 m, respectively. Assuming a depositional rate of 3 m/m.y., the age of the base of the Marra Mamba Iron Formation is constrained to between about 2670 and 2620 Ma. The distance between the base of the Griquatown Iron Formation and the base of the Kuruman Iron Formation is about 210 m (Beukes, 1980a). Assuming an identical rate of deposition of 3 m/m.y., the base of the Kuruman Iron Formation is about 2500 Ma, suggesting that the Kuruman Iron Formation is contemporaneous with the Dales Gorge Member rather than the Marra Mamba Iron Formation.

The Archean-Proterozoic boundary is defined as either a chronological boundary at 2500 Ma or as a lithological boundary coinciding with the development of cover sequences on a continental scale (Plumb and James, 1986). The U-Pb age of 2552 ±11 Ma obtained for zircon from the tuff unit in the Nauga Formation precisely delimits the time of deposition of the top of the Campbell Group. Therefore, in southern Africa, the former definition of a chronological 2500 Ma boundary would be placed, lithologically, within the transition between the carbonate and iron-formation sedimentation. In the latter case, the Archean-Proterozoic boundary would be the time at which regionally extensive cover rocks of the Transvaal and Griqualand West Sequences were unconformably deposited on the underlying Archean granite-greenstone and high-grade gneiss terranes on the Kaapvaal craton. The late Archean age for the Nauga Formation is therefore a minimum age estimate for the Archean-Proterozoic boundary in southern Africa and places the deposition of the extensive Campbell Group and Malmani Subgroup carbonate-platform sequences in the late Archean.

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