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Source: *The Journal of Geology*, Vol. 104, No. 4 (Jul., 1996), pp. 459-469

Published by: The University of Chicago Press

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New Pb-Pb Single Zircon Age Constraints on the Timing of Neoproterozoic Glaciation and Continental Break-up in Namibia¹

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ABSTRACT

Dating of single zircons from low-grade metamorphosed rhyolites in the Rosh Pinah Formation of the Gariep Belt in southwestern Namibia, using the Pb evaporation technique, yielded a primary crystallization age of 741 ± 6 Ma. Both the stratigraphic position and the geochemistry of the volcanic rocks indicate an early continental rift environment. The new data not only provide an age for the massive Zn-Pb-Cu sulfide mineralization associated with these volcanic rocks, but they also set a maximum age limit for Neoproterozoic continental break-up in southern Namibia. This age is statistically indistinguishable from a recently reported age of 748 ± 3 Ma for stratigraphically equivalent volcanic rocks in the northern rift of the Damara Belt, suggesting that the onset of the formation of the N-S-trending Adamastor ocean and of the NE-trending Khomas ocean in central and northern Namibia occurred at the same time. The volcanic unit directly overlies, in both rift grabens, a diamictite horizon with glaciogenic features. Our new results further constrain the age of this glacial epoch, which may be correlated with the Sturtian glaciation, to around 750 Ma.

Introduction

Continental break-up after the c. 1.1 Ga Kibaran event, that formed the Namaqualand-Natal metamorphic belt in southern Africa, led to the formation of the so-called Adamastor ocean (Hartnady et al. 1985) south of the São Francisco–Congo cratonic bridge, separating the cratons and surrounding early- to middle-Proterozoic belts of southern Africa from those of South America (figure 1). Some of the sediments and igneous rocks deposited in this oceanic basin occur as metamorphic rocks in the various Pan-African orogenic belts, specifically the Kaoko, Damara, and Gariep Belts in southwestern Africa and the Ribiera and Dom Feliciano Belts in the east of South America (figure 1). Recent studies on the metamorphic history of the Gariep Belt (Frimmel and Hartnady 1992; Frimmel 1995) suggest that the Adamastor ocean never evolved to a wide oceanic basin. Despite extensive studies, particularly on the Damara Belt in central Namibia (Miller 1983), the timing

of the rifting remains unresolved. Porada (1989), for instance, proposed a time span of >300 Ma for rifting and spreading in the Damara and Gariep Belts, and related it with the Katangan episode, at c. 900 to 750 Ma.

One of the important questions that arises in connection with the evolution of the Pan-African orogens is, whether the various basins represented by the different orogenic belts have evolved concurrently. Both the Gariep and Kaoko Belts follow roughly a N-S trend, parallel to the present-day South Atlantic coast line. In contrast, the Damara Belt (*sensu stricto*) branches off to the northeast and is therefore usually referred to as the intracontinental arm of the Damara Orogen (*sensu lato*). The timing of the opening of the N-S-trending basins represented by the Gariep and Kaoko Belts relative to that of the NE-trending basin of the Damara Belt, the so-called Khomas trough, is of importance for the reconstruction of the configuration of Proterozoic plates and forms the main focus of this paper.

The eastern portion of the Gariep belt is made up of predominantly metasedimentary units on a passive continental margin, above the basement rocks of the c. 1.1 Ga Namaqualand Metamorphic Complex. The older Gariepan strata contain pre-

¹ Manuscript received October 12, 1995; accepted January 28, 1996.

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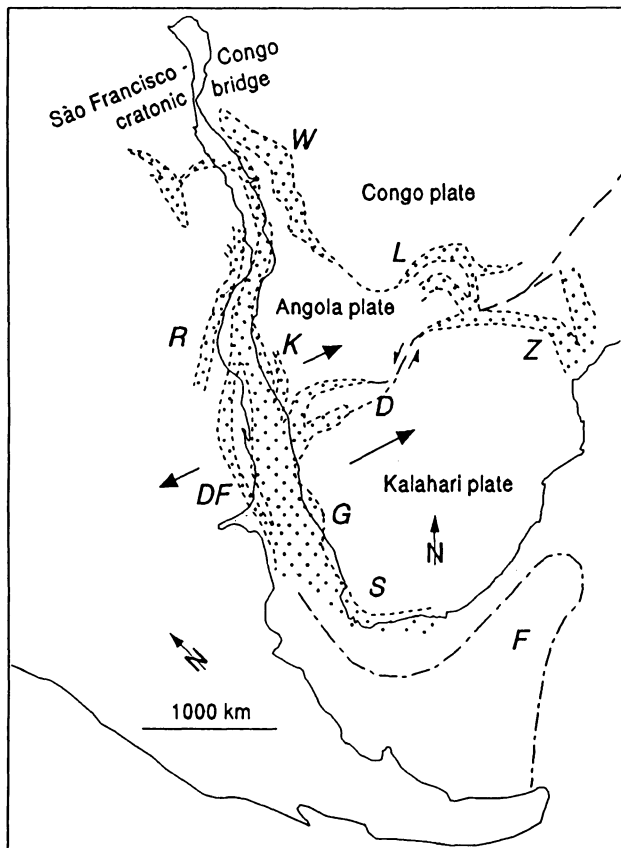


Figure 1. Approximately post-orogenic positions of the Pan-African rifts in western Gondwanaland (modified after Porada 1989); D—Damara Belt; DF—Dom Feliciano Belt; F—Falkland plateau; G—Gariiep Belt; K—Kaoko Belt; L—Lufilian Arc; R—Ribeira Belt; S—Saldania Belt; W—West Congolian Belt; Z—Zambezi Belt. Arrows indicate approximate vectors for plate movement during the opening of the Adamastor ocean.

dominantly felsic volcanic and volcanoclastic rocks that rest on top of a distinct diamictite horizon serving as a stratigraphic marker horizon. Locally, massive base metal sulfide mineralization is associated with this volcanic unit, which is known as the Rosh Pinah Formation, named after the only presently mined massive sulfide deposit in the area, around Rosh Pinah in southwestern Namibia.

The Rosh Pinah Formation reflects virtually the only magmatic activity in the external parts of the Gariiep Belt, except for a mafic dike swarm that cuts across the underlying basement and lower units of the Gariiep Belt. No geochemical data on the Rosh Pinah Formation has been published to date. This paper provides the first major, trace, and rare earth element data as well as preliminary isotope data of the Rosh Pinah Formation in order to

assess the tectonic setting of this important formation. We also present new single zircon age data that constrains the age of the Rosh Pinah Formation and thus indirectly also the minimum age of the underlying diamictite, for which a glacial influence is indicated. The combined geochemical and age data will not only be used to explain the tectonic setting of the economically significant massive sulfide mineralization in the Rosh Pinah Formation, but they will also provide evidence for the birth of the Adamastor ocean.

Geologic Setting

Regional Tectonic and Stratigraphic Setting. The Pan-African Gariiep Belt, stretching from Lüderitz in the southwestern part of Namibia to the northern part of the South African west coast, is divided into two major zones: the para-autochthonous Port Nolloth Zone in the east, representing a predominantly sedimentary passive continental margin, and the allochthonous, predominantly mafic Marmora Terrane in the west (figure 2). They are

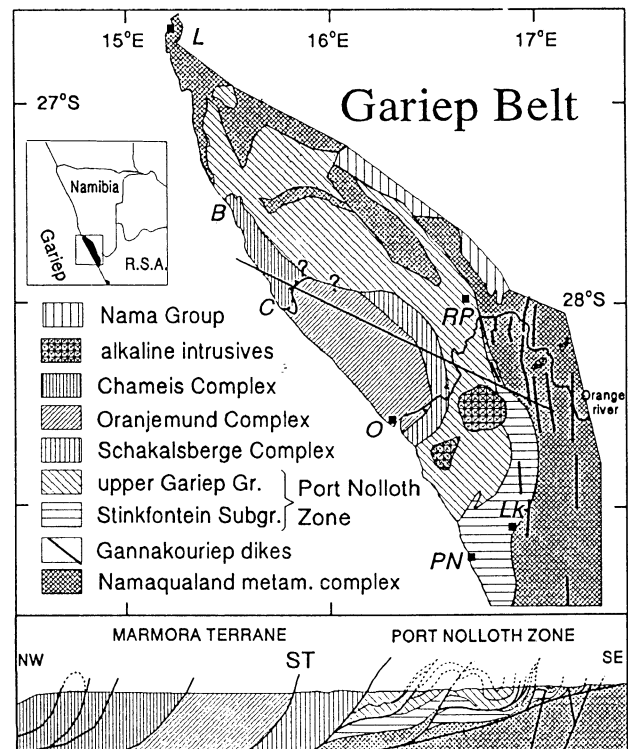


Figure 2. Simplified geological map of the Gariiep Belt, showing the position of the Rosh Pinah Zn-Pb-Cu sulfide deposit (RP), with NW-SE cross-section. A—Alexander Bay; B—Bogenfels; C—Chameis Bay; L—Lüderitz; Lk—Lekkering; O—Oranjemund; PN—Port Nolloth; ST—Schakalsberge Thrust.

juxtaposed along the arcuate, N-S- to southwest-trending Schakalsberge Thrust, along which the Marmora Terrane was thrust in a southeasterly direction over the Port Nolloth Zone (figure 2).

The Marmora Terrane consists of three tectonostratigraphic complexes (Frimmel and Hartnady 1992). These are, from southeast to northwest, the Schakalsberge Complex, the Oranjemund Complex, and the Chameis Complex (figure 2). Based on petrographic, structural and recent geochemical data (Frimmel et al. 1996), the tectonic setting of these three complexes can be described as follows: the Schakalsberge Complex represents oceanic islands or an aseismic ridge, capped by reef dolomite; the predominantly clastic Oranjemund Complex is turbiditic in places and was deposited on the slope of these islands (ridge); the Chameis Complex contains relics of mid-oceanic ridge material, together with oceanic island basalts, within an accretionary wedge. Thus the Marmora Terrane reflects the depositional environment of the Adamastor oceanic basin.

Information about the opening of this ocean can be obtained from the lower units of the Gariiep Group in the Port Nolloth Zone, which stretches from the coastal region south of the Orange river mouth, via Rosh Pinah, to the area between Bogenfels and Lüderitz (figure 2). The stratigraphy of the Gariiep Group (figure 3) starts with a basal conglomerate and quartzites belonging to the Lekkersing Formation, feldspathic quartzites and minor intermediate to felsic volcanic intercalations of the Vredefontein Formation, and calcareous feld-

spathic quartzites interbedded with phyllite and dolomitic limestone of the Gumchavib Formation (Von Veh 1993). All of these rocks, comprising the Stinkfontein Subgroup, accumulated on the west flank of an actively rising fault scarp, characterized by alluvial fans, alluvial plains, and fan deltas.

The Kaigas Formation unconformably overlies the Stinkfontein Subgroup. It is dominated by a diamictite deposited along the west flank of above-mentioned fault scarp. Intercalated greywacke shows normal grading and cross-laminations that indicate paleo-current directions from the east. These rocks represent talus, landslide, and debris-flow fans and pinch out rapidly toward the center of the basin in the west (Von Veh 1993). Evidence of glacial debris is indicated by clasts that penetrate and deform underlying laminations, bimodal clast distribution, and oversized erratic blocks in shaly beds. The locally developed Kaigas Formation is overlain by a predominantly calcareous sequence (\pm dolomitic marbles) with intercalated metapelites, quartzites, and metaconglomerates, which constitute the Hilda Subgroup (Von Veh 1993). This sequence, in turn, is unconformably overlain by the Numees Formation, which consists of thin-banded iron-formation, quartzite, and pelite beds, and a massive glaciogenic diamictite horizon that includes varved pelites containing dropstones. The stratigraphic top of the Gariiep Group is formed by the Holgat Subgroup, which comprises turbiditic metaarkoses, metagreywackes, metapelites, and marbles.

The occurrence of the predominantly volcanic Rosh Pinah Formation is restricted to an area that extends from Rosh Pinah for about 35 km to the northwest (figure 4). Stratigraphically, this formation occurs above fluvial siliciclastic deposits, comparable with the Lekkersing Formation, or in other places the Kaigas Formation diamictite. It is overlain by the shelf carbonates and intercalated clastic rocks of the Hilda Subgroup. Within the Rosh Pinah Formation, a proximal volcanic facies can be distinguished from a distal volcanoclastic facies. These volcanic facies include massive rhyolitic lava flows, felsic agglomerates, crystal tuffs and tuffites, ignimbrites, and intercalated sulfidic black shales, chert and dolomitic limestones. The distal facies is characterized by arkoses, calcarenites, and argillite with minor interbedded carbonate horizons, dark tuffitic shale, ferruginous shale and chert, minor felsic volcanic and pyroclastic rocks, and conglomerates. The facies become progressively carbonate-dominated, grading into the Hilda Subgroup with both time and increasing distance from the fault scarp.

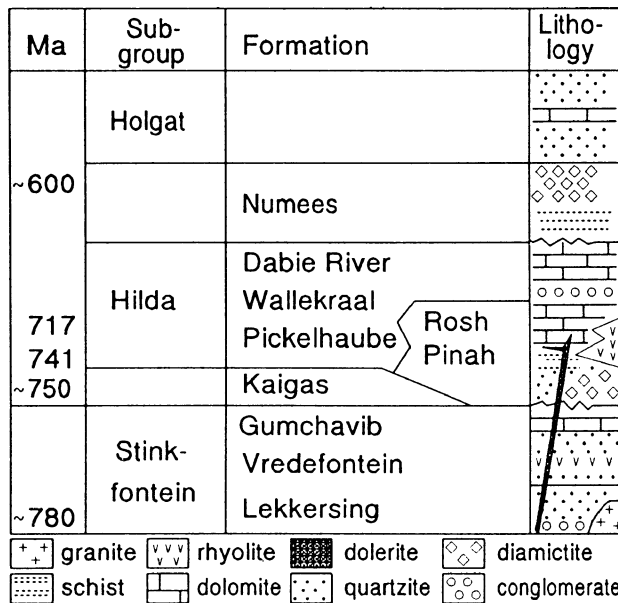
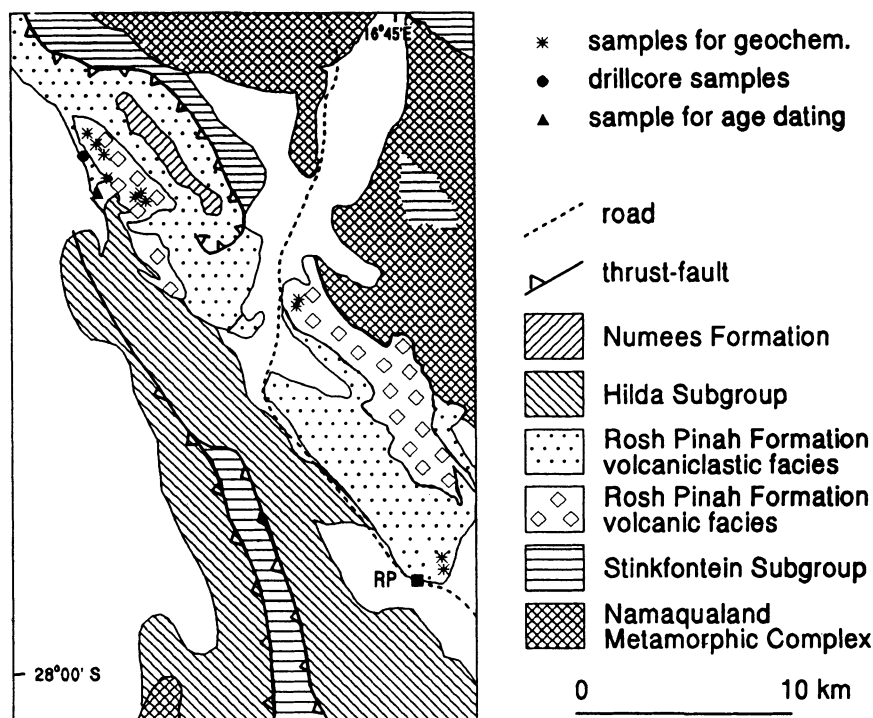


Figure 3. Stratigraphy of the Port Nolloth Zone; for sources of ages see text.

Figure 4. Simplified geological map of the area northwest of Rosh Pinah (RP) showing sample locations.



Structure and Metamorphism. The rocks deposited along the active fault scarp forming the eastern boundary of the Port Nolloth Zone were affected by inversion tectonics as a consequence of the continent-continent collision that resulted in the Pan-African orogeny, which culminated around 545 Ma (Frimmel 1995). The first and most penetrative deformation (D_1) produced open-to-isoclinal eastward-vergent folds and a penetrative s_1 schistosity. Regional metamorphic P-T conditions reached the peak, i.e., upper greenschist facies (albite-epidote-amphibolite facies), syntectonically with regard to D_1 . At the same time, the Marmora Terrane was thrust over the Port Nolloth Zone along the master fault, the Schakalsberge Thrust.

Within the Port Nolloth Zone and the underlying basement, an imbricate fan of thrust faults developed, the individual faults often being reactivated, previously formed growth faults. This transpressive phase was followed by a sinistral-wrenching phase (D_2), resulting in the formation of non-cylindrical, close, westward-verging back-folds and back-thrusts along the eastern margin of the Port Nolloth Zone. The Pan-African deformation style was mainly controlled by an existing bend in the continental margin. The change in orientation of the continental margin relative to the colliding plate during the closure of the Adamastor ocean led to a southward decrease in the wrench/

thrust ratio. Later deformation is of minor significance and related to sinistral transtension, leading to open gravity folds, normal faults, veins, and fractures (Von Veh 1993).

The Rosh Pinah Zn-Pb-Cu Sulfide Deposit. Page (1976) and later Van Vuuren (1986) described the petrography, geologic setting, and the structure of the Rosh Pinah deposit and suggested a volcano-sedimentary exhalative origin. This was further supported by Siegfried and Moore (1990). Evidence for such a genesis includes the fine grain size of primary sulfide minerals, some of which show relict framboidal as well as colloform textures, and the presence of sedimentary structures, such as soft sediment deformation and graded bedding, displaced by sulfide and gangue minerals, concordance with the stratigraphy, and rip-up clasts of ore-zone rock types in the overlying strata. Both lateral and vertical metal zonation trends in terms of Cu/(Pb + Zn) ratio have been noted (Siegfried and Moore 1990). The stratiform sulfide bodies are hosted by Mn- and Fe-rich dolomite within a feldspathic quartzite sequence of the Rosh Pinah Formation. The highest Pb and Zn concentrations (and thus the highest ore grade) are found at the top of the host dolomite layer and are associated with a marked barite anomaly, but the Cu concentration increases toward the bottom. Mineralization was accompanied by silicification and brecciation, as evidenced by dark sulfidic chert in the ore horizon

and by intense stockwork brecciation in the footwall quartzite.

Pan-African tectonism caused the reconstitution of the ore-zone sulfides. Mobilization of sulfides, barite, and dolomite occurred near D_1 thrusts that developed in the footwall quartzite. Recrystallization and mobilization of sulfides, accompanied by CO_2 -metasomatism, is also evident in D_1 and D_2 fold hinges. The upper parts of some of the ore bodies were later affected by supergene alteration.

Geochemistry of the Rosh Pinah Formation

Sample Description. Samples of felsic lava flows and crystalline tuffites were collected from the proximal volcanic facies of the Rosh Pinah Formation (figure 4). The metavolcanic rocks consist of microcline phenocrysts embedded in a very fine-grained matrix of quartz and biotite. Pyrite, pyrrhotite, sphalerite, and marcasite were identified in fresh samples. Zircon is a common accessory phase. Dark varieties of this rock type have a groundmass rich in very fine-grained graphite. Locally, the rock appears highly vesicular, with the vesicles being filled with calcite, quartz, chlorite, and secondary iron oxides or sulfides. The groundmass exhibits in places banding that probably reflects original flow or quench textures.

The volcanoclastic rocks consist of rounded-to-subangular detrital quartz clasts, angular K-feldspar clasts, and dark recrystallized volcanic glass fragments, all of which are embedded in a very fine-grained recrystallized quartz-sericite matrix with variable, but generally small amounts of epidote or calcite. Locally, detrital muscovite flakes and decimeter-size basement pebbles can also occur. The large proportion of angular K-feldspar (5–15 modal %) is explained as crystal tuff component reworked by fluvial activity and redeposited in a shallow marine, near-coastal environment.

A drill core (for location see figure 4) revealed the presence of mafic rocks underlying the felsic sequence. The amount available was limited, but three representative samples of metabasalt and a metagabbro sample could be included in the analysis. They are completely recrystallized to amphibolites with the equilibrium assemblage: edenitic amphibole–albite–biotite–chlorite–epidote–titanite–quartz–magnetite. Carbonate alteration is common in the form of cross-cutting calcite veins.

Methods. All analyses were carried out at the Department of Geological Sciences, University of Cape Town. Major and trace element concentrations were determined by conventional X-ray flu-

orescence techniques using a Siemens SRS-1 spectrometer for the analysis of the major elements and a Philips 1400 for that of the trace elements. The concentrations of the major elements were measured in fused $Li_2B_4O_7$ -pellets, those of the trace elements in pressed powder briquettes. Typical detection limits are below 0.01 wt % for the major elements and below 2 ppm for most trace elements. Rare earth element concentrations were obtained by gradient ion-chromatography using a Dionex 4000i instrument employing techniques described by le Roex and Watkins (1990). Rb, Sr, Sm, and Nd were separated by conventional ion-exchange techniques. Isotope ratios were measured on a VG Sector 7-collector mass spectrometer in multidynamic mode. The measured $^{87}Sr/^{86}Sr$ ratios are normalized to a $^{86}Sr/^{88}Sr$ ratio of 0.1194, and to a $^{87}Sr/^{86}Sr$ ratio of 0.71022 obtained for the NBS-987 standard during this study. The measured $^{143}Nd/^{144}Nd$ ratios are normalized to a $^{146}Nd/^{144}Nd$ ratio of 0.7219 and to a $^{143}Nd/^{144}Nd$ ratio of 0.51183 for the La Jolla standard. Total blanks were in the order of <10 pg Rb, Sr, Sm, and Nd, respectively, and no blank corrections were made to the data.

Results. The geochemical results obtained on selected representative samples of felsic metavolcanic, volcanoclastic, and mafic rocks are presented in table 1, which can be obtained from *The Journal of Geology* upon request, free of charge. The felsic volcanic rocks are high in SiO_2 (75.2–79.8 wt %) and have $Na_2O + K_2O$ contents of 6.4–9.6 wt %, typical of a rhyolite. The low total in sample HFG78 (table 1) can be ascribed to the presence of sulfur in the form of pyrite and probably also sphalerite, as indicated by elevated Zn concentrations. Sample HFG112 shows anomalously low Rb and Ba, and high Sr concentrations. This may be interpreted as a result of hydrothermal alteration. The volcanoclastic rocks are, in comparison to the metarhyolites, enriched in SiO_2 and Cr, because of detrital quartz and probably chromite, and they are lower in Al_2O_3 , Zn, and the high field strength elements.

The underlying metabasalts and metagabbros contain 47.3–51.4 wt % SiO_2 . They are hypersthene- and olivine-normative and are thus classified as olivine tholeiite. The relatively low totals (table 1) are explained by the presence of Fe^{3+} in the form of magnetite. The metagabbro (HFG124) is distinguished by having considerable higher Ni, Co, Cu, and Sr concentrations, but lower Rb and Ba concentrations than the metabasalts. No rocks of intermediate composition between the basalts and the rhyolites were found. In terms of their nor-

mative hypersthene:olivine:diopside ratios, the basalts are alkaline, but their Nb/Y ratios correspond to those typical of subalkaline basalts. Considering the relative mobility of Fe and Ca compared with that of Nb and Y, the latter characterization is preferred (Frimmel et al. 1996).

In the Nb-Zr-Y diagram of Meschede (1986), the metabasalts plot along the boundary between P-MORB and within-plate tholeiite (figure 5). A within-plate setting is favored by us because of the geological setting and also because of the distribution of Y, Nb, and Rb in the rhyolites (figure 6). From figure 5 it becomes evident, that the mafic rocks of the Rosh Pinah Formation were derived from a different magma source than the Gannakouriep mafic dike swarm studied by Ransome (1992).

The metabasalts have heavy rare earth element concentrations similar to those of a mid-oceanic ridge basalt, but they are slightly enriched with respect to the light rare earth elements (figure 7), which is in good agreement with a within-plate origin. The metabasalts show a negative Sr anomaly, whereas the metagabbro sample has a positive Sr anomaly and a relatively flat pattern in figure 7. Both are particularly enriched in Rb, a fact ascribed to the exchange with metamorphic fluids derived from the surrounding crustal rocks. This led to particularly high $^{87}\text{Rb}/^{86}\text{Sr}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of, respectively, 5.802 and 0.75907 (± 2) in the metabasalt (HFG122). The corresponding ratios in the metagabbro (HFG124) are 0.0424 and 0.71440 (± 2).

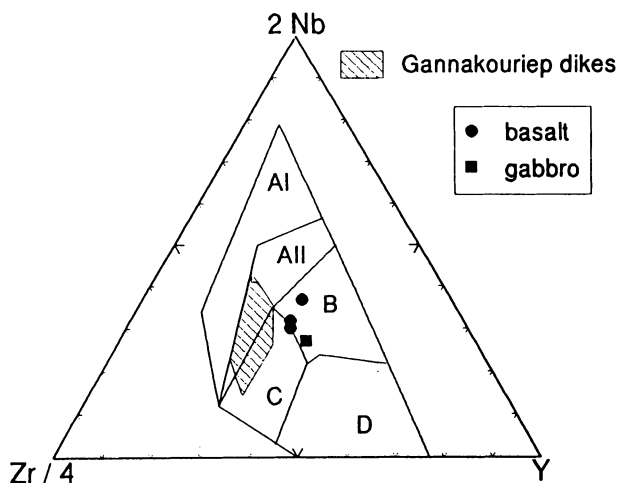


Figure 5. Zr-Nb-Y discrimination diagram (after Meschede 1986) for the Rosh Pinah Formation in comparison to the Gannakouriep dikes (Ransome 1992). Data fields are as follows: within-plate alkaline basalts (AI + AII), within-plate tholeiites (AII + C), P-MORB (B), N-MORB (D), volcanic arc basalts (C + D).

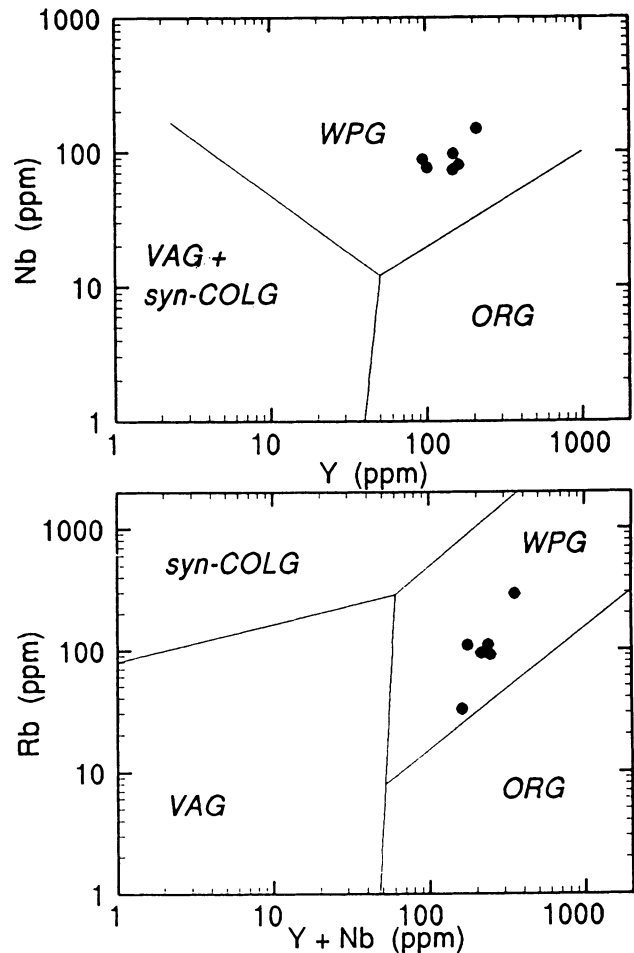


Figure 6. Nb-Y-Rb discrimination diagrams (after Pearce et al. 1984) for the Rosh Pinah Formation rhyolites. WPG—within-plate granite; syn-COLG—syn-collision granite; VAG—volcanic arc granite; ORG—ocean ridge granite.

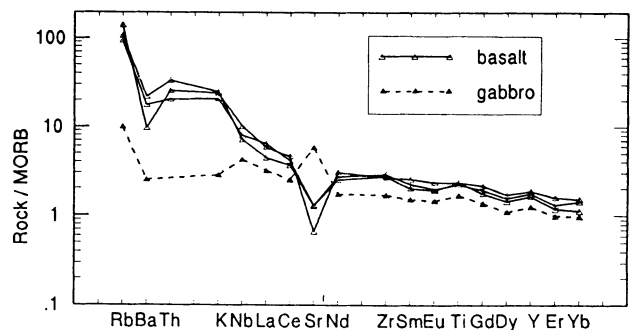


Figure 7. Trace and rare earth element patterns for mafic rocks from the Rosh Pinah Formation normalized to primitive mantle values of Sun and McDonough (1989).

No genetic or age inferences can be made from these isotope ratios, because the mafic rocks clearly did not remain closed systems with respect to Rb and Sr during metamorphism. The $^{147}\text{Sm}/^{144}\text{Nd}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios measured in the metabasalt (HFG122) are respectively 0.1526 and 0.51258 (± 1). The same ratios measured in the metagabbro (HFG124) are 0.1676 and 0.51274 (± 1), respectively. Based on the rare earth element distribution shown in figure 7, there is no reason for assuming significant exchange of Sm and Nd with the surrounding rocks. The ϵ_{Nd} -values of 2.93 and 4.68, calculated for an assumed age of 700 Ma, are therefore considered genetically significant and provide further evidence for a within-plate tectonic setting.

Single Zircon Age Data

Sample Description and Method. The zircon grains used in this study were separated from a dark grey, graphitic, vesicular metarhyolite, which occurs as irregularly shaped, 25–70 m thick body in a sequence of low-grade metamorphosed ignimbrites, about 50 m above an underlying metasedimentary sequence in the Rosh Pinah Formation. The sample locality (see figure 4) is c. 23 km northwest of Rosh Pinah (27° 48.23' S, 16° 37.05' E).

The individual zircon grains are euhedral, prismatic, and between 50 and 250 μm in size. There are virtually only two crystallographic forms developed, i.e., the prism {100} and the pyramidal form {101}. This is in accordance with the zircon typology of alkaline series rhyolites from anorogenic complexes (Pupin 1980). Under the optical microscope, most of the zircon grains appear clear, free of inclusions and homogenous. Cathodoluminescence imaging using a Leica CL and an Oxford Mono CL detector interfaced to a Cambridge Stereoscan S440 electron microscope at the Electron Microscope Unit of the University of Cape Town revealed recurrent growth zonation patterns (figure 8). With the help of these images, zircon grains that appear to represent one generation could be separated from such grains, that showed evidence of older cores.

We employed the single zircon evaporation technique, which involves the breakdown of zircon, ZrSiO_4 , to porous baddeleyite (ZrO_2) and the associated loss of mainly silica together with U, Th, Pb, and Hf along a reaction front progressing into the interior of the grain (Ansdell and Kyser 1993; Roddick and Chapman 1991; Roddick 1994). The analyses were carried out at the Laboratory for Geochronology, University of Vienna, using a

Finnigan MAT262 thermal ionization mass spectrometer, following modified procedures originally described by Kober (1987). Details of the applied procedures are given in Klötzli (1995) and Klötzli and Parrish (1995). Individual zircon grains were heated stepwise in a Re-double filament ion source arrangement to 1200–1300°C in order to strip off common Pb and radiogenic Pb components that have low activation energy and are therefore weakly bound to metamict zircon or inclusions. As soon as no “low-temperature” Pb or isobaric overlaps were observed (after 0–2 hrs), the zircon temperature was raised by 20°C and the Pb isotopic composition was measured either directly or the evaporated Pb was deposited stepwise on the cold ionization filament (15–45 minutes). Pb was analyzed using either static Faraday or dynamic ion counter data acquisition comprising at least 2 blocks with 10 scans, each with 4 seconds integration time and 2 seconds dead time, respectively. For subsequent data acquisition after each deposition step, the Re evaporation filament current was set to 1.2 A during the analysis to prevent Pb from evaporating from the ionization filament and being re-deposited on the evaporation filament. After each Pb analysis, the ionization filament current was raised to 4.5 A for a few seconds to strip off all remaining material deposited during the evaporation step. To test whether the Pb evaporation was indeed complete or the zircon has just fallen off the filament, the evaporation filament current was slowly raised to 3.8 A, with the ionization filament current set to 5.0 A, and the presence of zircon was confirmed by monitoring the Zr^+ -ion beam on mass 90. The measured $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{208}\text{Pb}/^{206}\text{Pb}$ ratios were corrected using factors derived from NBS SRM982 and NBS SRM983 standard measurements. The correction factors were individually determined for Faraday and ion counter procedures before and after the zircon analyses using the same data acquisition procedures as for the zircon analyses. Only high temperature steps (>1350°C) with $^{204}\text{Pb}/^{206}\text{Pb} < 0.0002$ were used for age calculations. Thus no common Pb correction had to be applied. Decay constants used are from Steiger and Jäger (1977). The ages reported are weighted-mean data calculated from at least 20 measured $^{207}\text{Pb}/^{206}\text{Pb}$ ratios. All errors reported are 2 standard errors of the mean (>95% confidence level).

Results. Six individual zircon grains were analyzed, one with four evaporation steps and the remaining grains with only one step (table 2). Two grains (GPS13 and GPS16) contained very high common Pb concentrations with $^{204}\text{Pb}/^{206}\text{Pb}$ ratios

Table 2. Single Zircon Age Data

Sample	Evaporation Temp. (°C)	No. of Blocks	$^{207}\text{Pb}/^{206}\text{Pb}$	Error (%)	Age (Ma)	Error (Ma)	$^{208}\text{Pb}/^{206}\text{Pb}$	Error (%)
GPS15	1501	3	.06381	1.36	735	29	.1462	6.02
GPS11	1410	6	.06372	2.75	732	58	.1513	1.89
GPS12/1	1413	11	.06402	.32	742	7	.2702	.31
GPS12/2	1434	14	.06361	2.32	729	49	.2592	2.05
GPS12/3	1443	3	.08117	1.31	1225	20	.3148	.48
GPS12/4	1460	6	.08680	2.74	1317	53	.3294	2.95
GPS14	1395	4	.10192	3.81	1663	70	.3650	2.90

of 0.0534 ± 0.0062 and 0.0343 ± 0.0058 , respectively, which precludes any age calculation. Two grains (GPS12 and GPS14) show evidence of inherited Pb components, probably inherited zircon cores. They define a minimum crystallization age for the precursor rock of ≥ 1663 Ma. The remaining grains (GPS11 and GPS15), together with the first two step data of GPS12 define a weighted mean age of 741 ± 6 Ma. This is interpreted as primary crystallization age. Both within one single crystal (GPS12) and between different grains, strongly variable U/Th ratios were found. No Th-rich inclusions are visible in the cathodoluminescence images (figure 8). As the compositional variation cannot result merely from differences in the crystallization age, it seems to demonstrate changing U/Th concentrations during zircon growth, which is probably reflected by the recurrent zonation shown in figure 8.

Discussion

Tectonic Setting of the Rosh Pinah Formation. All of the geochemical results presented here, including Sm-Nd isotope data, trace element and rare earth element concentrations, evidence a within-plate tectonic setting for the Rosh Pinah Formation. Thus the low-grade metamorphosed felsic and mafic rocks of the Rosh Pinah Formation are interpreted as expressions of a bimodal rift-related igneous activity, dominated by the eruption of rhyolitic melts. This is in agreement with the relatively thin (<1000 m) stratigraphic sequence overlying the basement (Siegfried and Moore 1990), and the presence of rapid lateral facies changes in the Rosh Pinah Formation, all of which suggest deposition during the early stages of a rifting event.

The eastern part of the Rosh Pinah Formation is strongly influenced by coarse fluvial deposits, whereas the western part is dominated by shallow marine deposits. The fallout of the partly subaerial volcanic activity, centered along a growth fault, is

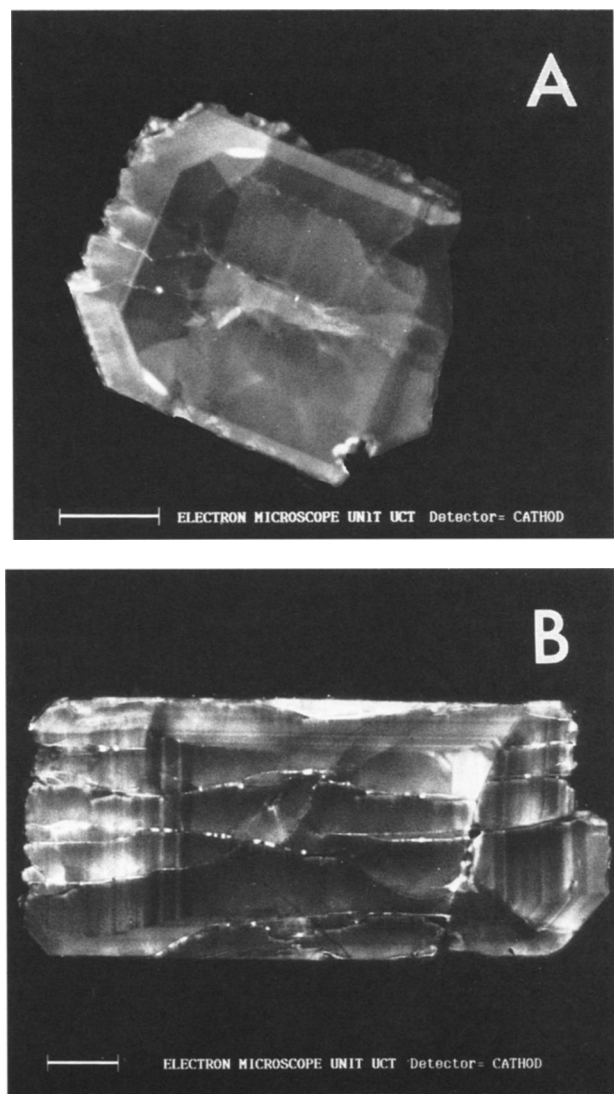


Figure 8. Cathodoluminescence images of zircon grains from Rosh Pinah Formation rhyolite: (A) euhedral overgrowth around inherited core; (B) single generation grain. Recurrent zonation probably due to varying U/Th ratios. The surface fractures are an artifact of the sample preparation. Scale bar = 30 μm .

thus found in the form of shallow marine tuff layers, as tuff horizons sandwiched between rhyolitic lava flows, and as crystal tuffs deposited in the fluvial environment and subsequently re-deposited to coarse clastic tuffites. Only after the deposition of the Rosh Pinah Formation, laterally more persistent, shallow marine platform carbonates began to dominate (Hilda Subgroup) before the basin evolved to a deeper-water environment (Numees Formation and Holgat Subgroup).

The rapid facies changes in the Rosh Pinah Formation may explain the variety in style of mineralization associated with the volcanic activity. The known ore bodies, though not located on top of the rhyolite pile as it is generally the case for volcanic-hosted massive sulfide deposits (Franklin et al. 1981), occur as stratiform lenses below the main volcanic pile in sedimentary strata. A more distal, in places Mn-rich, Fe-oxide facies can be distinguished from a proximal sulfide facies. Barite is abundant in or near the massive sulfide bodies. All of these features, together with the lateral and vertical metal zonation trends, are typical of the Zn-Pb-Cu group of volcanic-associated massive sulfide deposits (Franklin et al. 1981). A pre-orogenic age of the mineralization is also supported by the observation that the ore has experienced the same tectonic and metamorphic overprint as the host rocks. Thus we have no doubts that the formation of the Zn-Pb-Cu sulfide bodies is related to the felsic volcanism, for which an early rift setting is established.

Timing of Rifting. The magmatic crystallization age of 741 ± 6 Ma determined for single zircons in these embryonic rift-related rhyolites represents not only the best available constraint on the age of the Rosh Pinah massive sulfide deposit and other related base metal mineralization in the Rosh Pinah Formation, but it is also the first reliable date from the Gariiep Belt for continental break-up. Previously reported Rb-Sr ages for metavolcanic rocks in the Stinkfontein and Gariiep Groups of 662 ± 20 Ma and 686 ± 32 Ma (Allsopp et al. 1979) must be regarded as geologically meaningless and can be explained by partial resetting during the Gariiepan metamorphism dated at 545 Ma (Frimmel 1995). Similarly, our Rb-Sr isotope data do not allow any inferences about age to be made.

The new age for the Rosh Pinah Formation suggests that it is older than the mafic Gannakouriep dike swarm, for which Reid et al. (1991) determined an age of 717 ± 11 Ma. Some of the dikes crosscut the Stinkfontein Subgroup and, in places, they appear to extend into the carbonate rocks of the Hilda Subgroup. The Gannakouriep dikes have

distinctly different geochemical characteristics (Ransome 1992) than the Rosh Pinah Formation igneous units. Although the dike swarm is also related to crustal thinning, it has been derived from a different magma source (Frimmel et al. 1996) and probably reflects a more advanced stage of rifting.

Centers of shallow-level, felsic intrusive bodies in the basement are known from an area to the immediate east of the Gariiep Belt in southern Namibia (the older Bremen Complex), from the Richtersveld southeast of the Gariiep Belt in the northwestern Namaqualand (the Richtersveld Intrusive Suite), and from the southern Namaqualand (Klein Kogelfontein syenite and Biesiesfontein granite). These alkaline intrusive rocks have been dated around 920 Ma (Allsopp et al. 1979) and they are therefore post-orogenic with respect to the 1.0–1.1 Ga Namaqua metamorphic event. Based on the allegedly intrusive relationship between the 780 Ma Lekkersing granite and Stinkfontein Subgroup quartzites in the south of the Port Nolloth Zone (Allsopp et al. 1979), a relationship between the felsic volcanism in the Rosh Pinah Formation and these 920 Ma alkaline intrusives in the neighboring basement has been proposed in the past (e.g., Porada 1989; Siegfried and Moore 1990). Our new age data clearly shows, that such a relationship is not possible, and that rifting in the Gariiep Belt could not have started much earlier than c. 750 Ma. The allegedly intrusive contact between the Lekkersing granite and the lower Stinkfontein siliciclastic strata has never been documented and has been questioned by several workers (e.g., Reid et al. 1991). If this contact is not intrusive but erosional, the age of the Lekkersing granite would provide a maximum age of 780 Ma for the Stinkfontein Subgroup, which is in better agreement with our age for the Rosh Pinah Formation.

Metal Source. The immediate source of the ore constituents may be either the underlying rocks, contemporaneous magmas, or coeval seawater. The proximity of the ore horizon to volcanic rocks, as well as the relatively thin sediment thickness, suggest that volcanogenic-hydrothermal fluids were involved in the genesis of the base metal sulfide mineralization in the Rosh Pinah Formation rather than sediment-derived formation waters or seawater, as it is commonly inferred for sedimentary-exhalative deposits (Russel et al. 1981).

Unpublished Pb isotope ratios from the Rosh Pinah massive sulfide deposit and other occurrences in the Rosh Pinah Formation (Anglo American Prospecting Services Namibia Limited unpub. report 1984) are similar, supporting the idea that these occurrences are co-genetic. The model ages

are between 934 and 1107 Ma, similarly as those determined by Köppel (1978) for galena from Rosh Pinah (1065–1145 Ma). They are too old and suggest that some of the Pb was derived from the underlying basement rocks. Zircons from a basement inlier west of Rosh Pinah yielded a U-Pb age of 1870 ± 20 Ma (Allsopp et al. 1979), which conforms to the age of the calc-alkaline Vioolsdrif batholith east of the Gariep Belt (Allsopp et al. 1979; Reid 1979). The Pb isotope ratios obtained for the inherited zircon cores in this study indicate that the source rock for the Rosh Pinah Formation rhyolite must have been older than 1663 Ma, which is in accordance with the age of the underlying continental crust. It thus appears that the mid-Proterozoic basement rocks were also the most likely metal source. A crustal source of the Pb agrees with incipient continental rifting being the cause of the bimodal volcanism in the Rosh Pinah Formation.

Conclusions

New single zircon ages presented here constrain the timing of the initial Pan-African rifting in the mid-Proterozoic crust of southwestern Namibia and western South Africa at 741 ± 6 Ma. This age is very similar to a recently obtained single zircon U-Pb age of 748 ± 3 Ma for rhyolite lavas of the Upper Naauwpoort Formation in the early Damaran syn-rift Nosib Group in the Summas Mountains, northern Namibia (Hoffman et al. 1994). There the rhyolite lavas and tuffs overlie a diamictite (Okotjize Formation) similarly as the Rosh Pinah Formation overlies the Kaigas Formation diamictite. These ages for the Rosh Pinah and the Naauwpoort Formations can be taken as maximum ages for continental break-up. They are statistically indistinguishable, suggesting that rifting in the Gariep Belt and in the northern Damara Belt (*sensu stricto*) occurred at the same time. The births of the Adamastor ocean and of the intracontinental Khomas ocean were therefore coeval. If the closure of the Zambezi Belt, Lufilian Arc, and the West Congolian Belt during the Katangian episode was caused by the opening of the Adamastor ocean and subsequent drift of the Angola plate (figure 1), it could have happened only after 750

Ma. This is in good agreement with the minimum age of 750–700 Ma, suggested by Porada (1989) for the northward-directed compressional D₂ tectonic phase in the Lufilian arc.

The oldest diamictite horizon in the Gariep Belt, the Kaigas Formation diamictite, does not appear to be a local phenomenon but can be correlated with analogous horizons across the Pan-African belts of southwestern Africa. The minimum age for these diamictite horizons is constrained by the recent ages obtained for the overlying felsic volcanic rocks. The maximum age for this diamictite is given by a recent U-Pb zircon age of 757 ± 1 Ma for a syenite that intruded the underlying strata in the northern Damara Belt (Hoffman et al. 1994). It thus appears that these glacial deposits in both northern and southern Namibia are roughly of the same age. Their age, geochemistry, and structural setting support the contention of Eyles (1993), that these glacial deposits are worldwide, often associated with the uplifted flanks of rifted margins. A proposed age of c. 750 Ma for the Kaigas Formation diamictite and its equivalents in the Damara Belt is at the upper end of the age bracket of 700–750 Ma proposed for the Sturtian glacial epoch by Meert and van der Voo (1994). The younger diamictite horizon of the Numees Formation in the Gariep Belt may be correlated with the Vendian global glacial epoch (Vendian), for which Meert and van der Voo (1994) proposed an age bracket of 580–625 Ma. However, no reliable age data are available yet for this period from Namibia.

ACKNOWLEDGMENTS

Gold Fields Namibia Ltd. is thanked for access to their grant area and for making drill core available. Visits of the Rosh Pinah mine and surrounding outcrops were made possible by Imcor Zinc Ltd. S. Richardson and A. P. le Roex assisted with isotope and rare earth element analyses, respectively, and D. Gerneke helped with cathodoluminescence imaging. Funding by the Foundation for Research Development (grant to HEF) and by the Austrian Science Foundation (grant to USK) is gratefully acknowledged. J. Meert and an anonymous reviewer are thanked for their helpful comments.

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