The Bushmanland Group supracrustal succession, Aggeneys, Bushmanland, South Africa: Provenance, age of deposition and metamorphism

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ABSTRACT

The central portion of the structurally complex and poly-metamorphosed Namaqua Province of western South Africa is underlain by a series of pelitic and psammitic metasediments, termed the Bushmanland Group, which is host to world class Broken Hill-type Pb-Zn-Cu-Ag deposits at Aggeneys. Geochemical, U-Pb SHRIMP zircon geochronology and Sm-Nd isotopic determinations of the metasediments at Aggeneys were undertaken to determine the age and nature of the provenance, as well as to confine the age of deposition of the Bushmanland Group in this area.

The metasediments were derived from moderately-weathered granodiorites to granites, or their volcanic equivalents, with ~2.65 to ~2.25 Ga Sm-Nd T_{DM} model ages. Mixed sources are likely from the geochemical signatures of the metasediments as well as the varied detrital zircon ages, with two main age groupings present of ~2.12 to ~1.97 Ga and ~1.88 Ga to ~1.64 Ga. The upper part of the succession has a narrower compositional range and was derived from a more mafic provenance than the basal portion. The provenance is likely to have been a combination of ~1.8 Ga Gladkop Suite granitic gneisses found to the west and the ~2.1 to ~1.9 Ga intrusive and volcanosedimentary rocks of the Richtersveld Subprovince to the northwest. The metasediments were deposited in a passive margin setting and underwent extensive reworking in addition to recycling.

The time of deposition of the Bushmanland Group is constrained between the age of the youngest detrital zircon (~1.64 Ga) and the onset of the regionally extensive Kibaran Orogeny at ~1.2 Ga. Metamorphic overgrowths and rims on detrital zircons record two distinct events, the ~1.21 to ~1.18 Ga Kibaran Orogeny, characterised by extensive granitic magmatism, peak D_2 deformation and peak upper amphibolite facies grade M_2 metamorphism, and the more ubiquitous ~1.04 to ~1.01 Ga Namaquan Orogeny characterised by weaker M_3 metamorphism.

Introduction

The Broken Hill-type Pb-Zn-Cu-Ag deposits at Aggeneys, South Africa are world-class examples of an important mineralisation type (Beeson, 1990; Walters, 1996). The Aggeneys deposits are situated in the central region of the Proterozoic Namaqua Sector of the Namaqua-Natal Belt, a belt of highly deformed medium- to high-grade metamorphic rocks to the south and west of the Archean Kaapvaal Craton of South Africa (Figure 1). The structural complexity of the region and the high grade of metamorphism has led to complications in correlating rocks, particularly those of the supracrustal successions, from one area to another (Joubert, 1986; Moore, 1989) and has led to complicated tectonic models for the area (summarized in Joubert, 1986). The importance in determining the tectonic evolution of the area lies not only in its economic potential as hosts of Broken Hill-type deposits, but also in its role in the amalgamation of the southern African

continental crust during the construction of the Rodinian supercontinent at ~1.2 to ~1.0 Ga (Thomas *et al.*, 1993a, 1994).

Numerous geochronological studies have been undertaken on the Cu-rich Okiep District of the western Namaqua Province (Clifford *et al.*, 1975; 1981; 1995; 2004; Robb *et al.*, 1999; Figure 1), but only a few (*e.g.* Armstrong *et al.*, 1988) have been done on the economically significant Bushmanland Group metasedimentary succession around Aggeneys, with previous age determinations (Reid *et al.*, 1987; 1997a) having focused on whole rock radiogenic isotope systematics to postulate the age of deposition of the Bushmanland Group. Furthermore, there has been protracted debate as to the provenance, basement and source of base metals to the supracrustal succession (Duncan *et al.*, 1984; 1985; Watkeys, 1986; Watkeys *et al.*, 1988a; b; Moore, 1989; Moore *et al.*, 1990; Lipson, 1990; Reid *et al.*, 1997a; b). These arguments have

Figure 1. Location of the study area in South Africa (modified after Van Aswegen *et al.*, 1987). The upper left inset shows the tectonic setting of the Namaqua-Natal Province (after Thomas *et al.*, 1993a).

suggested that the present-day basement, a series of granitic gneisses termed the Achab and Hoogoor Gneisses, are older than the Bushmanland Group and acted as the basement and provenance to the metasediments and source of the base metal mineralisation. These arguments have been made based on the geochemical and isotopic characteristics of the gneisses despite the highly deformed nature of both the gneisses and the metasediments and the structural contact between the two which makes the relationship unclear (Watkeys, 1986). Lipson (1990) argued for a Paleoproterozoic provenance to the northwest of the Bushmanland Group with its deposition on an unknown basement.

In light of this debate, it was decided to re-examine the geochemistry and geochronology of the Bushmanland Group metasediments. This paper examines the geochemistry of the metasediments using the data of Lipson (1990), and incorporates new trace element and Sm-Nd isotope data in order to assess the provenance and tectonic setting of the Bushmanland Group in the Aggeneys area. In addition, single zircon geochronological analyses on detrital zircons within the Bushmanland Group were obtained to give a better

estimate of the age of deposition of the metasediments as well as an indication of the age of the source region.

Regional Geological Setting

The economically important deposits, near the town of Aggeneys within the Northern Cape Province of South Africa, ~110 km to the northeast of the town of Springbok and ~80 km to the west of Pofadder (Figure 1), are the biggest source of lead and zinc metal in the country (Ryan *et al.*, 1986). They are known as, from west to east, Black Mountain, Broken Hill, Big Syncline and Gamsberg (Figure 2). The deposits become progressively zinc-rich and lead-poor from the Cu-rich Black Mountain deposit in the west (Ryan *et al.*, 1986) to the large tonnage, low-grade Zn-rich Gamsberg deposit in the east (Rozendaal, 1986). The prominent inselbergs and ranges of hills which characterise the arid landscape of the area are formed by the metavolcanic-metasedimentary units of the Bushmanland Group that usually occur as major, often overturned, synformal infolds in the associated granitic gneisses (Joubert, 1974). Apart from geochemical characteristics the metasedimentary nature of the metapelites and metaquartzites is confirmed by the presence of heavy

Figure 2. Simplified geological map of the Bushmanland area around Aggeneys and Gamsberg showing the various inselbergs and the distribution of the various granitic gneisses and the Bushmanland Group supracrustal succession (after Reid *et al.*, 1997a). The localities of the samples for the geochronological study are shown.

mineral layers and the presence of other sedimentary features, such as cross bedding within the metaquartzite units (Lipson *et al.*, 1986).

The deposits occur in the northwestern portion of the highly deformed and metamorphosed Namaqua-Natal Belt of southern Africa (Figure 1), an area of reworked and juvenile ~1.2 to 1.0 Ga crust deposited on, or intruded into older ~2.0 Ga Eburnian crust represented by the Richtersveld Subprovince to the northwest of Aggeneys (Thomas *et al.*, 1993a). Medium- to high-grade metamorphism accompanied polyphase deformation of the original sedimentary and volcanic rocks (Thomas *et al.*, 1993a) due to collision or accretion of the Belt with the Kaapvaal Craton at ~1.2 to ~1.1 Ga (Jacobs *et al.*, 1993).

Previous radiometric dating on the rocks of the Namaqua Sector (Nicolaysen and Burger, 1965; Clifford *et al.*, 1975; 1981; 1995; 2004; Reid, 1979a; Barton, 1983; Reid *et al.*, 1997a; Robb *et al.*, 1999; Clifford *et al.*, 2004) have revealed a pattern of ~1.21 to 0.95 Ga magmatism, tectonism and metamorphism (Thomas *et al.*, 1993a; 1994) associated with a major period of continental growth and accretion and the amalgamation of the Rodinian supercontinent (Hoffman, 1991). Within this ~1.21 to ~0.95 Ga period two major tectono-magmatic episodes are recognised, namely one at ~1.21 to ~1.17 Ga, and a second at ~1.06 to ~1.03 Ga, termed the Kibaran and Namaquan orogenies respectively (Robb *et al.*, 1999).

The meta-volcanosedimentary supracrustal succession throughout the Bushmanland Subprovince is represented by the Okiep and Bushmanland Groups

which occur within the Okiep and Aggeneys Districts respectively. These compositionally variable sequences comprise chemogenic units, meta-arenites and minor intercalated volcanic rocks. The Bushmanland Group includes ferruginous quartzite, shale, calc-silicate assemblages and amphibolite along with the associated Pb-Zn-Cu-Ag massive sulphide mineralisation at Aggeneys and Gamsberg (Robb *et al.*, 1999). The Okiep Group includes quartzite, cordierite-bearing parageneses, granulites and calc-silicate rocks (Clifford *et al.*, 2004). These metasediments and metavolcanics are intruded by, and/or rest on voluminous granitic gneisses predominantly represented by the Little Namaqualand Suite (Blignault *et al.*, 1983) that obliterated any present-day traces of a pre-existing basement. The metasediments are thus preserved as rafts surrounded and intruded by voluminous granitic gneisses.

The age of Bushmanland Group deposition had previously been constrained between ~2.0 to ~1.65 Ga (Reid *et al.*, 1987; 1997a). Single zircon SHRIMP U-Pb ages of ~2.0 to ~1.8 Ga were obtained from detrital zircons (Armstrong *et al.*, 1988) in a heavy mineral layer in a quartzite at Froneman se Kop at Aggeneys (Lipson *et al.*, 1986; Figure 2). Reid *et al.* (1987) obtained a Sm-Nd isochron age of 1649 ± 90 Ma from the Koeris Formation amphibolite overlying the Bushmanland Group. As the volcanic rocks of the Koeris Formation constitute the youngest geological succession in the area (Geological Staff Black Mountain, 1996; McClung *et al.*, 2002) (Table 1), their age is thought to provide a good estimate for the upper age of deposition of the

Bushmanland Group. In addition, single zircon U-Pb SHRIMP ages of ~2.0 Ga were obtained from the Achab Gneiss (Armstrong *et al.*, 1988), which had been interpreted as the basement to the Bushmanland Group (Moore, 1977; Watkeys, 1986).

The Aggeneys District has been subjected to three major metamorphic and five deformational events (Lipson, 1978; Stedman, 1980; Ryan *et al.*, 1986; Colliston *et al.*, 1989; Lipson, 1990; Hoffmann, 1993; Geological Staff Black Mountain, 1996; Colliston and Schoch, 2003). Peak prograde metamorphism (M_2), which attained upper amphibolite facies grade metamorphic conditions of 690°C at 4 kbar (Lipson, 1978; Rozendaal, 1978; Waters, 1986; 1987; 1989; Hoffmann, 1993; Willner, 1995), was related to peak D_2 deformation represented by recumbent isoclinal north-east plunging folds (F_2) (Ryan *et al.*, 1986), and associated thrusting, that dominate the structural pattern of the metasediments and is responsible for tectonic duplication. The third phase of deformation (D_3), which accompanied M_3 metamorphism, resulted in large-scale, open, asymmetric (F_3) folds striking east-north-east (Ryan *et al.*, 1986). The fourth phase of deformation (D_4) is represented by northerly-trending monoclinical folds and faults oriented northerly to northwesterly (Stedman, 1980). Northeasterly-trending strike-slip faults and shear zones characterise D_5 deformation (Ryan *et al.*, 1986; Colliston and Schoch, 2003).

The Namaqua Province is a HT/LP province with pressures not exceeding 6 kbar (Willner, 1995). Willner (1995) suggested near isobaric heating prior to peak temperature conditions. D_2 deformation occurred due to thrusting and crustal stacking (Joubert, 1974; Moore, 1977; Watkeys, 1986; Van Aswegen *et al.*, 1987). The retrograde PT-path indicates a definite pressure decrease with lower temperatures with the later metamorphic event (M_3) determined to be 550 to 600°C at 2.5 kbar (Willner, 1995). The rocks of central Bushmanland thus show a clockwise P-T-t path as opposed to the anti-clockwise P-T-t path determined for the granulite facies grade rocks to the west in the Okiep District (Waters, 1989; Willner, 1995).

Stratigraphic Nomenclature

The complex structural pattern of the Aggeneys District has led to difficulties in correlating stratigraphic units from area to area. Some workers (Colliston *et al.*, 1986; 1989; 1991; Praekelt and Schoch, 1997; Praekelt *et al.*, 1997; Colliston and Schoch, 1998) have argued that correlation between areas is not feasible and have devised a plethora of stratigraphic names in different areas where different successions have been mapped. Other workers (Moore, 1989; Lipson, 1990), have, however, argued for a simpler, ~1000 m thick succession that has undergone extensive tectonic duplication and stacking due to thrusting and deformation. Consequently, different workers have applied different stratigraphic columns and stratigraphic names in different areas (Table 1).

The Bushmanland Group developed locally around the Pb-Zn-Cu-Ag mineralisation in the Aggeneys District consists predominantly of aluminous schists interspersed with lesser quartzite, calc-silicate assemblages, amphibolites and iron formations. The supracrustal succession structurally overlies a series of granitic gneisses that generally include grey augen gneiss overlain by pink gneisses of the Hoogoor Suite. Regionally, the Bushmanland Group is subdivided into the Wortel and Kouboom Subgroups and capped by the Koeris Formation (McClung *et al.*, 2002) (Table 1). Previously the Bushmanland Group had been subdivided into a number of formations comprising various units or members (Rozendaal, 1975; Lipson, 1978; 1990) based on local mapping. McClung *et al.* (2002) argued that, from regional mapping, the Bushmanland Group should be subdivided into two major subgroups comprising a number of formations. The Wortel Subgroup comprises a basal aluminous metapelitic schist, termed the Namies Schist Formation, overlain by a clean white quartzite and pelitic schist, termed the Pella Quartzite and Pelitic Schist Formations respectively. McClung *et al.* (2002) recognised a regional unconformity above the Pelitic Schist Formation that separated the Wortel Subgroup from the overlying Kouboom Subgroup. The base of the Kouboom Subgroup is a dark quartzite termed the Broken Hill Quartzite Formation. Locally, such as at Gamsberg (Rozendaal, 1975) and at Aggeneys (Lipson, 1978; 1990; Ryan *et al.*, 1986), the two quartzite horizons with intervening pelitic schist have been included into one formation, variably given different names by different workers (Table 1) and the unconformity below the dark quartzite not identified. Above the Broken Hill Quartzite Formation at the base of the Kouboom Subgroup are a series of pelitic schists, iron formations and calc-silicates that host the massive sulphide Pb-Zn-Cu-Ag mineralisation. This has been termed the Gams Formation regionally, but at Aggeneys has been termed the Aggeneys Ore Formation by Ryan *et al.* (1986) and further subdivided into the Ore Schist and Shaft Schist Formations by Lipson (1978; 1990), each comprising a number of different lithological units (Table 1). The Gams Formation of the Kouboom Subgroup is unconformably overlain by a series of quartz-sericite schists, conglomerates, amphibolites and leucocratic gneisses termed the Nousees Mafic Gneiss by Rozendaal (1975) at Gamsberg, but termed the Koeris Formation regionally by McClung *et al.* (2002). While this formation has been included into the Bushmanland Group in the past (Table 1), its sharply erosive unconformable contact, which can cut down to the Namies Schist level in the underlying supracrustal succession, suggests that it is significantly younger and should not be included in the Bushmanland Group (McClung *et al.*, 2002).

As this study uses samples from the Broken Hill Mine at Aggeneys the local stratigraphic subdivision of the Bushmanland Group by Lipson (1990) at Aggeneys will be used, as this subdivides the succession into smaller

Table 1. Selected stratigraphic columns for the Bushmanland Group on a regional scale (SACS, 1980; McClung *et al.*, 2002), and in the Aggeneys-Gamberg District (Rozendaal, 1975, Lipson, 1978, 1990; Ryan *et al.*, 1986).

Bushmanland Group	Gamsberg		Aggeneys		Aggeneys	Regional	Regional	
	Rozendaal (1975)		Lipson (1978, 1990)		Ryan <i>et al.</i> (1986)	SACS (1980)	McClung <i>et al.</i> (2002)	
	Formation	Member	Formation	Unit			Subgroup	Formation
	Nousees Mafic Gneiss	Amphibolite	Grey Gneiss		Amphibolite and Leucocratic Gneiss	Quartz-muscovite Schist and Conglomerate Units		Koeris Fm.
		Schist and Conglomerates						
		C Member	Shaft Schist	Lower Footwall Schist				
				Upper Footwall Schist				
	Gams Fm.	B Member	Ore Schist	Lower Orebody	Aggeneys Ore Fm.	Gams Fm.	Kouboom	Gams Fm.
			Ore Equivalent Schist (Lateral Equivalent)	Intermediate Schist				
		A Member		Upper Orebody				
				Hangingwall Schist				
	Pella Quartzite	Dark Quartzite	Broken Hill Quartzite	Dark / Lower Quartzite	White Quartzite Fm.	Metaquartzite Unit		Broken Hill Quartzite Fm.
		Pelitic Schist		Median Schist				Pelitic Schist Fm.
		White Quartzite		White / Upper Quartzite			Wortel	Pella Quartzite Fm.
	Namies Schist		Namies Schist		Aluminous Schist Fm.	Namies Schist		Namies Schist
	Haramoep Gneiss				Pink Gneiss Fm.	Hoogoor Gneiss		Hoogoor Gneiss
			Basal Gneiss		Augen Gneiss Fm.	Aroams Gneiss		Achab Gneiss

^a The thick black line indicates that the contact between the gneisses and metasedimentary succession is typically structural in nature.

units rather than the broad regional subdivisions. Nevertheless, recognition of the units and formations within the Wortel and Kouboom Subgroups based on the regional classification by McClung *et al.* (2002) (Table 1) is also applied in general discussions and in certain cases. An example of the latter is the use of the Koeris Formation instead of Lipson's Grey Granoblastic Leucocratic Gneiss (Figure 3; Table 1). The regional subgroups will be referred to in discussions of overall geochemical and geochronological trends in the Bushmanland Group. The stratigraphic succession has been overturned at Broken Hill (Lipson, 1990), so that, for *e.g.*, the Dark, or Lower Quartzite is found stratigraphically above the White or Upper Quartzite (Figure 3; Table 1).

Petrography of the Succession

The Bushmanland Group is an approximately 1000 m thick succession subdivided at the Broken Hill Mine,

Aggeneys (Lipson, 1990), from oldest to youngest, into the Namies Schist, Broken Hill Quartzite, Ore Schist, Shaft Schist and Koeris Formations (Figure 3; Table 1). The overall succession has been overturned at the Broken Hill Mine (Lipson, 1990). The ore bodies are stratabound in nature (Ryan *et al.*, 1986; Rozendaal, 1986), and are mineralogically complex, containing chalcopyrite, galena, sphalerite, pyrite and pyrrhotite as the most common sulphide minerals (Ryan *et al.*, 1986). The mineralisation at Aggeneys is believed to have been deposited syngenetically (Rozendaal, 1982; Ryan *et al.*, 1986; Moore, 1989; Lipson, 1990; Moore *et al.*, 1990; Hoffmann, 1993). The metapelitic schists consist of sillimanite, biotite, garnet, quartz, muscovite, alkali feldspar and cordierite, with magnetite and ilmenite as the predominant oxides, and apatite, sphene, tourmaline, rutile, anatase, monazite and zircon present in accessory amounts. The stratigraphy is given by Lipson (1990) and is summarized in Figure 3.

Figure 3. Stratigraphic column at the Broken Hill Mine, Aggeneys. Due to overturning the units have names based on the structural succession found at the mine (modified after Lipson, 1990 and McClung, 2006).

The Namies Schist is a strongly foliated, coarse-grained, grey-green to pink quartzitic biotite-garnet-sillimanite schist with sillimanite and biotite locally developed in large concentrations (Ryan *et al.*, 1986; Lipson, 1990). It contains a greater concentration of garnet, cordierite, staurolite and zircon, but less sillimanite, biotite and muscovite than the Shaft Schist.

The Broken Hill Quartzite Formation, comprised of two distinct quartzite horizons (Figure 3), forms the resistant caps to the ranges of hills in the area. The two quartzites are separated into two approximately parallel ridges by an irregular, discontinuous, foliated, banded garnet-sillimanite-biotite-muscovite schist termed the Median Schist (Ryan *et al.*, 1986; Lipson, 1990). The Formation may have either a sharp or gradational

contact with the overlying Ore Schist Formation (Ryan *et al.*, 1986). The quartzites are of a glassy nature, with minor biotite and muscovite scattered throughout and containing a variety of minor constituents, including thin micaceous muscovite-rich bands, as well as magnetite-, pyrite- and garnet-rich zones, and more rarely tourmaline-, gahnite- and diopside-bearing bands (Moore, 1989). The Dark Quartzite contains more mica and accessory minerals than the White Quartzite, giving rise to its dark nature. Heavy mineral layers, composed of magnetite and biotite, and rich in zircon (Lipson, 1990), along with other sedimentary features, such as cross bedding, are also present (Lipson *et al.*, 1986).

The economically significant Ore Schist Formation (Ryan *et al.*, 1986; Lipson, 1990), containing the massive sulphide and barite deposits associated with iron formations, consists of a succession of quartz-muscovite-garnet-biotite-sillimanite schists (Figure 3), interbanded in places with thin units of micaceous quartzite, calc-silicate rocks and banded iron formations. The Lower Ore Body is significantly more Zn-rich than the Upper Ore Body, and has a smaller metal content (Hoffmann, 1993). The ore bodies and Intermediate Schist grade laterally into the Ore Equivalent Schist (Figure 3) comprised of biotite, garnet, sillimanite, muscovite and quartz.

Light grey to red garnet quartzites, consisting of microbands of quartz, with lesser biotite and muscovite, alternating with garnet-biotite-apatite-rich microbands, are associated with the ore bodies. The rock has a high quartz component ($\geq 70\%$) with subordinate garnet and biotite, along with minor apatite, sillimanite, magnetite, alkali feldspar and trace amounts of gahnite, sulphide (mostly sphalerite), chlorite, zircon and zirconian staurolite (Hoffmann, 1993).

The Shaft Schist is developed in the structural footwall of the Broken Hill orebody (Figure 3), but rarely outcrops due to its soft nature and negative weathering characteristics (Lipson, 1990). It is a well-foliated, coarse-grained grey-green graphitic, sulphidic sillimanite-biotite schist. The top of the Kouboom Subgroup is terminated and not well exposed in the Aggeneys area, but drilling has revealed that the Shaft Schist is probably capped by a sequence of muscovite schist, amphibolite and conglomerate (Ryan *et al.*, 1986). This sequence is well developed at Gamsberg, where prominent conglomeratic and amphibolitic horizons occur and have been termed the Koeris Formation (Rozendaal, 1978; McClung *et al.*, 2002; Table 1). The Koeris Formation has been found at stratigraphic levels beneath those of the Namies Schist in certain areas (McClung *et al.*, 2002).

Geochemistry

Previous Work

Lipson (1990) and Frimmel *et al.* (1993) concluded that, apart from some minor variations in the more mobile elements, there have been no significant element transfers across lithological banding during medium- to

high-grade metamorphism beyond that which could be expected during metamorphism. The effects of the peak upper amphibolite facies grade of metamorphism on the geochemistry of the metapelitic schists and quartzites will be assumed to be isochemical. Lipson (1990) argued that alteration associated with the mineralisation is restricted to the vicinity of the ore bodies, but noted a greater hydrothermal component within the stratigraphic footwall than in the hanging wall. Stumpfl (1979) and Rozendaal and Stumpfl (1984) described manganese haloes around the Broken Hill and Gamsberg deposits related to the sulphide ore bodies. Hoffmann (1993) investigated the petrology, geochemistry and metamorphism of the Lower Ore Body at the Broken Hill Mine.

Methodology

Lipson (1990) undertook an extensive and exhaustive lithogeochemical examination of the Bushmanland Group metasediments using XRF-derived whole-rock data, from which the samples used in this study were derived. The major element data used is exclusively that of Lipson (1990). Trace element characterization makes use of both the XRF data of Lipson (1990) and new trace element data derived from inductively coupled plasma mass spectrometry (ICP-MS).

Lipson (1990) gives a detailed account of the sampling procedure, sample preparation and analytical techniques employed for these samples. XRF analyses were performed on Siemens SRS-1 and Phillips PW1400 wavelength dispersive XRF spectrometers. The data of Lipson (1990) used in this paper are recalculated volatile-free.

Twenty-eight Sm-Nd analyses of the metasediments were undertaken. Of these analyses, 23 are from borehole core from the Broken Hill Mine, with the remaining five samples from the Namies- and Shaft-type Schists, and the White- and Dark-type Quartzites, which show similar characteristics to the lithologies at Broken Hill (Lipson, 1990). The Nd isotopic compositions of selected samples of the Bushmanland Group metasediments were determined in the radiogenic isotope facility of the Department of Geological Sciences, University of Cape Town, using a VG Sector 54 seven-collector thermal ionization mass spectrometer. Single HF/HNO₃/HClO₄ dissolutions of 100 mg of natural (unspiked) whole rock powders were used for measuring Nd isotopic compositions. Rare earth element (REE) separation using cation-exchange columns and Nd isotopic determination using a double filament technique are those of Zindler (1980) and Zindler *et al.* (1979).

The $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were corrected for fractionation using $^{146}\text{Nd}/^{144}\text{Nd} = 0.72190$ (O'Nions *et al.*, 1977) and normalized to $^{143}\text{Nd}/^{144}\text{Nd} = 0.511840$ for the La Jolla standard. Repeat analyses of the La Jolla standard gave $^{143}\text{Nd}/^{144}\text{Nd} = 0.511807$. Total system blanks for Nd were found, in general, to be below 200pg and were considered negligible. The $2s_{\text{mean}}$ errors on in-

Table 2. Selected major element analyses for various lithologies of the Bushmanland Group (after Lipson, 1990). All measured in weight percentage.

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	H ₂ O-	LOI	Total
Core Shaft Schist (SS)													
ALP 57	61.28	0.74	18.90	6.68	0.05	1.69	0.19	0.35	4.72	0.07	0.41	4.92	100.00
ALP 59	61.91	0.74	18.95	6.66	0.03	1.72	0.12	0.24	4.19	0.05	0.35	5.07	100.03
ALP 136	70.17	0.66	16.19	5.18	0.04	1.10	0.10	0.16	2.94	0.04	0.28	3.53	100.39
ALP 157	62.75	0.64	18.93	5.96	0.02	1.47	0.25	0.49	4.35	0.07	0.49	4.45	99.87
Core Shaft-type Schist (STS)													
ALP 422	47.47	1.13	29.12	10.06	0.22	2.42	0.10	0.10	5.05	0.08	0.40	5.25	101.40
ALP 424	55.92	0.99	22.28	7.83	0.11	2.48	0.13	0.11	5.18	0.08	0.52	5.12	100.75
Core Namies Schist (NS)													
ALP 39	82.03	0.47	9.34	4.10	0.09	0.36	0.04	0.07	2.36	0.04	0.33	1.24	100.47
ALP 62	69.51	0.62	15.43	5.95	0.11	0.66	0.12	0.14	4.38	0.07	0.28	2.55	99.82
ALP 63	69.78	0.62	15.23	6.10	0.12	0.37	0.11	0.11	4.53	0.04	0.13	2.29	99.43
ALP 122	70.27	0.80	14.59	8.30	0.18	0.76	0.15	0.22	3.40	0.08	0.27	1.28	100.30
Surface Namies-type Schist (NTS)													
ALP 401	70.72	0.60	14.51	5.58	n.d. ^a	0.95	0.09	0.11	2.82	0.04	0.58	4.25	100.25
ALP 403	65.46	0.53	12.97	4.23	n.d.	0.93	0.06	0.09	1.89	0.03	0.47	13.61	100.27
White Quartzite (WQ)													
ALP 40	98.61	0.06	1.07	0.67	n.d.	0.05	n.d.	0.03	0.31	0.02	0.07	0.22	101.11
ALP 67	98.78	0.05	1.12	0.79	n.d.	0.09	n.d.	0.12	0.31	0.04	0.03	0.29	100.62
White-type Quartzite (WTQ)													
ALP 432	99.75	0.02	0.45	0.18	n.d.	n.d.	n.d.	n.d.	0.09	n.d.	0.04	0.19	100.72
ALP 435	97.09	0.07	1.11	1.09	n.d.	n.d.	0.02	0.05	0.38	n.d.	0.07	0.31	100.19
Dark Quartzite (DQ)													
ALP 42	94.88	0.13	2.30	2.10	0.04	0.13	0.02	0.05	0.49	n.d.	0.13	0.36	100.63
ALP 69	96.17	0.07	1.55	1.65	0.03	0.05	0.02	0.04	0.51	n.d.	n.d.	0.29	100.38
Dark-type Quartzite (DTQ)													
ALP 437	96.29	0.08	1.97	0.76	n.d.	n.d.	0.12	0.34	0.55	0.02	0.09	0.45	100.67
ALP 448	92.68	0.26	3.59	1.57	n.d.	0.02	0.06	0.21	1.12	0.04	0.09	0.57	100.21
Median Schist (MDS)													
ALP 41	70.85	0.70	14.56	8.26	0.16	0.70	0.07	0.12	3.32	0.04	0.26	1.29	100.33
ALP 68	71.18	0.66	13.95	7.47	0.23	0.62	0.16	0.09	3.48	0.08	0.30	1.57	99.79
Median-type Schist (MDTS)													
ALP 436	69.45	0.71	13.45	7.53	0.04	0.96	0.42	0.73	4.92	0.10	0.25	2.00	100.56
ALP 449	71.89	0.83	13.19	5.75	0.10	1.60	0.74	0.42	3.24	0.07	0.23	2.66	100.72
Hangingwall Schist (HS)													
ALP 43	70.50	0.74	15.97	7.57	0.22	0.68	0.09	0.13	2.84	0.02	0.27	0.92	99.95
ALP 101	71.95	0.69	15.11	5.92	0.48	0.99	0.15	0.11	3.51	0.06	0.21	0.90	100.08
ALP 163	66.26	0.67	17.40	7.20	0.63	0.63	0.13	0.07	3.18	0.07	0.42	3.60	100.26
Intermediate Schist (IS)													
ALP 76	62.83	0.82	20.48	6.35	0.30	0.92	0.08	0.14	5.62	0.06	0.40	2.07	100.07
ALP 177	66.27	0.75	17.53	6.75	0.48	0.73	0.09	0.10	4.74	0.07	0.31	2.78	100.60
Ore Equivalent Schist (OES)													
ALP 173	62.75	0.84	18.58	9.49	0.36	1.11	0.12	0.06	3.23	0.03	0.33	3.24	100.14
ALP 175	63.68	0.81	18.12	8.38	0.30	0.94	0.12	0.06	3.86	0.06	0.41	3.26	100.00
ALP 189	64.40	0.79	17.65	6.39	0.17	1.90	0.18	0.35	4.93	0.08	0.35	2.90	100.09
ALP 198	74.88	0.38	9.54	9.89	0.32	0.29	0.06	0.10	1.63	0.08	0.36	2.43	99.96
Upper Footwall Schist (UFS)													
ALP 51	60.91	0.89	20.57	10.00	0.28	1.08	0.14	0.09	3.96	0.05	0.28	1.81	100.06
ALP 52	62.09	0.87	18.96	8.50	0.51	1.34	0.23	0.15	4.79	0.04	0.31	1.77	99.56
ALP 134	62.65	0.90	20.49	6.95	0.08	1.73	0.09	0.09	4.30	0.05	0.31	2.39	100.03
ALP 179	56.41	1.00	22.71	8.50	0.43	0.95	0.09	0.07	5.87	0.03	0.37	3.89	100.32

^a n.d. – not determined or below detection limits

Figure 4. Major element plots for the Bushmanland Group metasediments at the Broken Hill Mine, Aggeneys. (a) TiO₂ vs. SiO₂. (b) Al₂O₃ vs. SiO₂. (c) Al₂O₃ vs. SiO₂ for the Shaft Schist from various boreholes at the Broken Hill Mine. (d) TiO₂ vs. Al₂O₃. (e) A-CN-K ternary plot (after Nesbitt and Young, 1984; 1989). (f) K₂O-MgO-Na₂O ternary plot illustrating the K-enrichment and Na-depletion of the metasediments.

Figure 5. Trace element plots for the Bushmanland Group metasediments. (a) Th/Sc vs. Zr/Sc indicating a large degree of sediment recycling (after McLennan *et al.*, 1990; 1993). (b) Th/Sc vs. Sc illustrating the contributions from a mafic provenance (represented by high Sc contents and low Th/Sc ratios) as opposed to a more felsic provenance (low Sc contents and high Th/Sc ratios) for the metasediments. (c) The Th-Sc-Zr/10 tectonic discrimination diagram of Bhatia and Crook (1986) for the Bushmanland Group metaquartzites.

run statistics for $^{143}\text{Nd}/^{144}\text{Nd}$ were generally less than 0.0001. In determining chondrite uniform reservoir (CHUR) model ages the $^{143}\text{Nd}/^{144}\text{Nd}$ value of 0.512638 of Hawkesworth and van Calsteren (1984) and the $^{147}\text{Sm}/^{144}\text{Nd}$ value of 0.1967 for CHUR (today) of Jacobsen and Wasserburg (1980) were used. For determination of depleted mantle reservoir (DM) model ages the depleted mantle curve of DePaolo *et al.* (1991) was used.

Results

A few samples of the Namies Schist have higher SiO_2 contents of >80 wt%, compared to the majority with SiO_2 <72 wt % (Figure 4; Table 2), suggesting a sub-group of higher mineralogical maturity. For an individual horizon, such as the Shaft Schist, there is a general increase in SiO_2 from northwest to southeast within the Broken Hill Mine area (Figure 4c), as also noted by Lipson (1990), reflecting an increase in mineralogical maturity and decrease in the proportion of unstable detrital grains such as feldspar and volcanic rock fragments (Bhatia, 1983). Lipson (1990) noted that the tendency for quartzite to thin southwards through

Aggeneys is matched by progressively cleaner separation in that direction of silica in quartzite from alumina in schist, indicating south-directed progradation over tens of kilometers.

The Namies and Median Schists have similar compositions and tend toward arkosic compositions, and are more sandy and quartzose in nature than the Shaft or Ore Schist Formation metapelites. The Namies Schist has higher $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios than the Shaft Schist, indicating a greater degree of sediment maturity (Bhatia, 1983) than the more clay-rich Shaft Schist. In addition, the Shaft Schist has a smaller compositional major element range than the Namies Schist (Figure 4a and b).

Lipson (1990) defined the Namies-type and Shaft-type Schists as the regional equivalents of the Namies and Shaft Schists respectively as these lithologies, developed at Wortel, Namiesberg and elsewhere within the Aggeneys District away from the Broken Hill Mine at Aggeneys, show similar geochemical characteristics to those developed at Broken Hill (Figure 4). Similarly, clean and dark-coloured quartzites developed in the Wortel and Namiesberg areas have been termed the White-type and Dark-type Quartzites by Lipson (1990).

Table 3. Selected trace element analyses for the metapelitic schists and quartzites of the Bushmanland Group. All measured in parts per million (ppm).

SAMPLE	Rb	Ba	Th	U	K	Nb	La	Sr	P	Hf	Zr	Ti	Y	Sc
Core Shaft Schist (SS)														
ALP 57 ^a	186	450	20.7	4.45	50108	12.0	43.8	59.7	493	5.19	177	927	12	14
ALP 59 ^a	187	404	20.4	4.96	44481	14.1	44.1	44.0	352	6.22	212	937	14	16
ALP 136	199	276	14	n.d. ^b	31211	14	24	15	282	n.d.	347	826	20	15
ALP 157	231	559	15	4.6	46180	13	36	49	493	n.d.	180	801	26	17
Core Shaft-type Schist (STS)														
ALP 422	342	573	33	n.d.	53611	40	70	8.9	564	n.d.	410	1415	40	27
ALP 424	289	726	21	5	54991	25	43	15	564	n.d.	259	1240	44	24
Core Namies Schist (NS)														
ALP 39 ^a	112	217	13.6	2.52	25054	12.4	44.3	5.83	282	8.12	294	588	24	5.0
ALP 62	232	3358	17	n.d.	46498	16	44	22	493	n.d.	286	776	42	10
ALP 63 ^a	208	3413	19.3	4.54	48091	16.3	50.2	13.4	282	5.5	192	776	28	11
ALP 122	223	414	14	n.d.	36095	19	42	21	564	n.d.	486	1002	29	14
Surface Namies-type Schist (NTS)														
ALP 401	195	486	15	n.d.	29937	14	30	23	282	n.d.	338	751	25	15
ALP 403	181	252	18	n.d.	20064	15	29	17	211	n.d.	416	664	30	13
White Quartzite (WQ)														
ALP 40 ^a	15.9	23.7	3.03	0.66	3291	1.77	10.70	0.93	141	2.49	92.0	75	5	1
ALP 67	17	24	n.d.	n.d.	3291	2.1	8	n.d.	282	n.d.	101	63	7	n.d.
White-type Quartzite (WTQ)														
ALP 432	5.3	4.5	n.d.	n.d.	955	n.d.	5	n.d.	n.d.	n.d.	50	25	3	n.d.
ALP 435	23	43	n.d.	n.d.	4034	3.1	11	3.5	n.d.	n.d.	280	88	8	1
Dark Quartzite (DQ)														
ALP 42 ^a	27.7	43.6	8.1	1.53	5202	4.33	23.00	1.04	n.d.	5.41	206	163	7	2
ALP 69	26	48	3.8	n.d.	5414	n.d.	12	2.1	n.d.	n.d.	119	88	8	n.d.
Dark-type Quartzite (DTQ)														
ALP 437	32	64	6.2	n.d.	5839	4.4	16	8.9	141	n.d.	166	100	7	1
ALP 448	55	232	10	n.d.	11890	6.5	12	14	282	n.d.	213	326	12	4
Median Schist (MDS)														
ALP 41 ^a	165	264	16.8	3.0	35245	17.3	37.5	6.54	282	6.4	223	876	14.9	8
ALP 68	213	410	12	n.d.	36944	18	34	17	564	n.d.	345	826	34	10
Median-type Schist (MDTS)														
ALP 436	285	609	12	n.d.	52231	18	34	70	704	n.d.	551	889	28	11
ALP 449	199	705	17	n.d.	34396	17	31	83	493	n.d.	295	1039	37	16
Hangingwall Schist (HS)														
ALP 43 ^a	170	403	22.4	2.94	30150	18.5	52.00	5.55	141	5.10	178	927	21.9	12
ALP 101	194	636	19	n.d.	37262	17	n.d.	15	423	n.d.	309	864	36	13
ALP 163	175	392	19	3.9	33759	16	n.d.	15	493	n.d.	201	839	41	16
Intermediate Schist (IS)														
ALP 76	307	2049	15	n.d.	59662	19	38	33	423	n.d.	228	1027	29	19
ALP 177	242	611	14	n.d.	50320	17	36	21	493	n.d.	238	939	42	18
Ore Equivalent Schist (OES)														
ALP 173 ^a	205	309	22.0	3.07	34290	23.1	50.9	6.80	211	6.11	215	1052	30.4	19
ALP 175	236	432	19	n.d.	40978	19	28	8.1	423	n.d.	298	1014	36	18
ALP 189	269	788	18	n.d.	52337	18	35	30	564	n.d.	277	989	33	18
ALP 198	113	985	13	n.d.	17304	11	n.d.	16	564	n.d.	225	476	20	9
Upper Footwall Schist (UFS)														
ALP 51	290	727	24	n.d.	42040	22	41	13	352	n.d.	229	1114	31	20
ALP 52 ^a	205	511	20.7	2.93	50851	20.1	49.5	25.4	282	5.00	171	1089	27.1	12
ALP 134	258	503	22	n.d.	45649	22	n.d.	20	352	n.d.	239	1127	28	22
ALP 179	319	664	17	n.d.	62316	24	37	15	211	n.d.	227	1252	33	21

^a ICP-MS analysis (this study), the rest Lipson (1990); ^b n.d. not determined or below detection limits

The Bushmanland Group metasediments have intermediate to high K_2O , intermediate SiO_2 and Al_2O_3 , low Fe_2O_{3T} and TiO_2 , and intermediate to low Nb, Rb and Th contents suggestive of a felsic igneous provenance rather than the low major element and high SiO_2 , Y, Nb, Rb, Th, Ba and Zr contents of a recycled provenance (Lacassie *et al.*, 2004). TiO_2 and Al_2O_3 correlate with each other for all the metapelitic schists and quartzites (Figure 4d). As the TiO_2/Al_2O_3 ratios of basaltic rocks are considerably higher than those for granitic rocks the TiO_2/Al_2O_3 ratios of between 3 and 6 for the metasediments indicates that they were derived from a predominantly granitic to granodioritic provenance. The low La/Th ratio (1.8) of the Bushmanland Group suggests a strongly fractionated, felsic provenance (Lipson, 1990). In addition, the high Th/Sc, Zr/Th, La/Sc and Ti/Zr ratios, in excess of upper continental crustal (UCC) values (McLennan *et al.*, 2006), indicate derivation from a felsic igneous provenance, which would be richer in Th and La, than mafic igneous or clay-dominated provenances, rich in Sc and Cr (Condie and Wronkiewicz, 1990; McLennan and Taylor, 1991; McLennan *et al.*, 1993).

Weathering trends of rocks of granitic / rhyolitic to granodioritic composition give rise to rocks of similar composition to those of the metapelitic schists and quartzites, which tend toward the composition of kaolinite (Figure 4e). Lipson (1990) argued that the degree of weathering did not proceed fully to the kaolin stage due to Rb/ K_2O ratios that, although exceeding that of average shale, are not as high as in kaolinite. The schists are notably Na-depleted (Figure 4f), and fall along the advanced weathering trend, either as having been derived from illite or smectite-bearing clays (Lipson, 1990; Hoffmann, 1993; Figure 4e), or as a consequence of Na-depletion and Al-enrichment associated with some form of alteration (*cf.* Willner *et al.*, 1990), be it provenance derived or post-deposition. The high Th/Sc ratios of >1 for the Namies and Shaft Schists, above upper crustal values of 0.79 (Taylor and McLennan, 1985; Figure 5a), also suggest that the metasediments were derived from a provenance that had undergone a significant degree of weathering, with subsequent reworking.

The metapelitic schists and quartzites are K-enriched and Na-depleted relative to typical shale compositions,

Figure 6. Trace element concentration (spider) diagrams and rare earth element (REE) plots for the Bushmanland Group metasediments. (a) NASC-normalised spider diagram. (b) Chondrite-normalised REE plot using the chondrite values of Nakamura (1974) with additional values from Boynton (1984). (c) NASC-normalised REE plot.

Table 4. REE contents of the Bushmanland Group metapelitic schists and quartzites determined by ICP-MS.

Sample	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Namies Schist (NS)														
ALP 39	44.3	83.0	11.3	38.3	6.91	1.64	5.61	0.91	4.62	1.00	2.69	0.45	2.90	0.49
ALP 63	50.2	101.0	13.6	46.4	8.52	1.95	6.98	1.15	5.74	1.17	2.85	0.44	2.66	0.43
White Quartzite (WQ)														
ALP 40	10.7	23.8	2.71	9.99	1.8	0.38	1.53	0.22	1.14	0.19	0.48	0.07	0.44	0.07
Dark Quartzite (DQ)														
ALP 42	23.0	48.0	5.35	19.2	3.64	0.48	2.72	0.36	1.64	0.25	0.66	0.10	0.75	0.12
Hangingwall Schist (HS)														
ALP 43	52.0	105.0	13.9	47.2	8.80	1.50	6.92	1.03	4.73	0.95	2.41	0.40	2.51	0.43
Ore Equivalent Schist (OES)														
ALP 173	50.9	110.0	13.6	48.7	8.78	1.15	7.08	1.08	5.82	1.19	3.45	0.55	3.74	0.59
Upper Footwall Schist (UFS)														
ALP 52	49.5	104.0	12.8	43.4	8.01	1.25	6.00	0.99	5.28	1.22	3.39	0.58	3.65	0.60
Shaft Schist (SS)														
ALP 57	43.8	80.8	10.7	35.5	6.37	1.02	4.56	0.69	3.04	0.55	1.23	0.19	1.14	0.20
ALP 59	44.1	81.5	10.6	35.3	6.34	1.04	4.66	0.71	3.10	0.58	1.32	0.20	1.28	0.22
	(La/Ce) _N	(Ce/Ce*)	(La/Sm) _N	(Eu/Eu*)	(Gd/Yb) _N	(La/Yb) _N	ΣREE							
NS	1.31 to 1.40	0.86 to 0.90	3.64 to 3.96	0.78 to 0.81	1.54 to 2.09	10.22 to 12.62	204 to 243							
WQ	1.18	1.02	3.67	0.70	2.77	16.26	53.5							
DQ	1.26	1.00	3.90	0.47	2.89	20.5	106.3							
HS	1.30	0.90	3.65	0.59	2.20	13.85	247.8							
OES	1.22	0.97	3.58	0.51	1.51	9.10	256.6							
UFS	1.25	0.96	3.81	0.55	1.31	9.07	240.7							
SS	1.42 to 1.43	0.86 to 0.87	4.24 to 4.29	0.58 to 0.59	2.90 to 3.19	23.03 to 25.70	190 to 191							
NASC						6.7								
PAAS						9.1								

such as the North American Shale Composite (NASC) (Gromet *et al.*, 1984) or the Post Archean Australian Shale (PAAS) (McLennan, 1989) (Figure 4f), a feature also noted by Moore (1989) for the metapelitic schists and quartzites on a regional scale for the western Namaqua Province.

The Namies Schist and Broken Hill Quartzite Formations of the Wortel Subgroup have higher La, Nb, Zr, Sm and Th/Sc, and lower Th, Ti, Cr, Sc and Ti/Nb than the Ore Schist and Shaft Schist Formations of the overlying Kouboom Subgroup (Figure 5b). The Shaft Schist has an exceptionally high S, Cr and V content. Lipson (1990) argued that an anoxic reducing depositional environment may be deduced for the Shaft Schist due to its high S and C content.

The quartzites plot exclusively in the passive margin field of the greywacke tectonic discrimination diagrams of Bhatia and Crook (1986) due to sediment recycling and / or reworking that has increased their Zr contents (Figure 5c). Lipson (1990) argued that a passive continental margin environment may be deduced from the extreme silica purity and sheet-like morphology of the quartz arenitic Broken Hill Quartzite Formation and from the elevated alumina concentrations of the Namies and Shaft Schists.

Relative to the NASC, and plotted according to the order of Wood *et al.* (1979) (Figure 6a), the metasediments show relatively flat to slightly

fractionated patterns, with most samples strongly depleted in Ba, Sr and Ti and with lower Nb and P contents, and slight enrichment in the light rare earth elements (LREE), Zr and Hf indicating derivation from a more fractionated, quartzofeldspathic provenance than that which gave rise to the NASC. Winchester and Max (1989) noted that passive margin profiles are similar to post-Archean continental shale profiles, such as NASC or PAAS, and therefore have a flat trend.

Chondrite-normalised REE patterns (Figure 6b) exhibit typical LREE-enriched, HREE-depleted sediment patterns with strong negative Eu anomalies ($Eu/Eu^* < 1$) for the metasediments, with a leveling off toward Lu and moderate HREE fractionation ($(Gd/Yb)_N = 1.5$ to 3.0) (Table 4). The Dark Quartzite has a higher REE content than the White Quartzite due to a larger heavy mineral content. The former also has a larger negative Eu anomaly than the latter. Relative to NASC (Gromet *et al.*, 1984) (Figure 6c) the metapelitic schists and quartzites have flat REE patterns with slight LREE enrichment and HREE depletion, being more fractionated than either NASC or PAAS (Table 4). The Namies Schist and the White Quartzite have positive Eu anomalies, whereas the Shaft Schist has markedly negative Eu anomalies and is more fractionated in its REE pattern than the Namies Schist relative to NASC. The metasediments show more fractionated signatures than NASC in their REE patterns (Figure 6c), suggesting more fractionated

Table 5. Sm-Nd isotopic data for the Bushmanland Group

Sample	Lithology	Sm ppm	Nd ppm	Sm/Nd	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$f^{\text{Sm/Nd}}$	$\epsilon_{\text{Nd}(0)}$	$^{143}\text{Nd}/^{144}\text{Nd}(t)^a$	$\epsilon_{\text{Nd}(t)}$	T_{DM} Ma
ALP 39	NS	7.0	38.9	0.180	0.11315	0.51166	-0.42	-19.9	0.51047	-2.76	2251
ALP 41	MDS	7.5	40.4	0.186	0.11756	0.51153	-0.40	-22.43	0.51029	-6.22	2558
ALP 43	HS	8.8	47.6	0.185	0.11731	0.51155	-0.40	-22.04	0.51032	-5.78	2520
ALP 52	UFS	8.5	47.4	0.179	0.11354	0.51154	-0.42	-22.24	0.51035	-5.19	2441
ALP 53	BGZ	7.3	40.8	0.179	0.11253	0.51147	-0.43	-23.60	0.51029	-6.36	2521
ALP 57	SS	6.1	34.2	0.178	0.11243	0.51148	-0.43	-23.41	0.51030	-6.14	2503
ALP 59	SS	6.6	36.7	0.180	0.11287	0.51147	-0.43	-23.60	0.51028	-6.43	2529
ALP 63	NS	8.7	48.1	0.181	0.11438	0.51159	-0.42	-21.26	0.51039	-4.39	2385
ALP 67	WQ	1.6	9.2	0.174	0.11224	0.51154	-0.43	-22.24	0.51036	-4.93	2410
ALP 68	MDS	7.7	41.8	0.184	0.11604	0.51145	-0.41	-23.99	0.51023	-7.47	2641
ALP 75	IF – UOB	3.1	7.2	0.431	0.26965		0.37				
ALP 76	IS	8.7	50.0	0.174	0.10991	0.51143	-0.44	-24.38	0.51027	-6.60	2516
ALP 101	HS	7.6	42.5	0.179	0.11338	0.51147	-0.42	-23.60	0.51028	-6.53	2542
ALP 122	NS	8.8	49.2	0.179	0.11350	0.51162	-0.42	-20.68	0.51043	-3.62	2319
ALP 125	MDS	5.5	20.0	0.275	0.17359	0.51193	-0.12	-14.63	0.51010	-9.93	
ALP 127	OES	7.7	41.8	0.184	0.11604	0.51147	-0.41	-23.60	0.51025	-7.08	2611
ALP 134	UFS	9.3	53.1	0.175	0.11124	0.51146	-0.43	-23.80	0.51029	-6.29	2504
ALP 136	SS	5.2	29.1	0.179	0.11301	0.51144	-0.43	-24.19	0.51025	-7.04	2577
ALP 141	SS	5.2	28.9	0.180	0.11379	0.51128	-0.42	-27.31	0.51008	-10.34	2838
ALP 147	IS	9.9	53.7	0.184	0.11670	0.51152	-0.41	-22.63	0.51029	-6.24	2551
ALP 164	HS	10.2	56.0	0.182	0.11536	0.51151	-0.41	-22.82	0.51030	-6.16	2531
ALP 172g	OEGQ	7.2	32.3	0.223	0.14155	0.51180	-0.28	-17.16	0.51031	-5.87	2838
ALP 177	IS	8.2	44.2	0.186	0.11781	0.51157	-0.40	-21.65	0.51033	-5.49	2502
ALP 402	NTS	4.4	24.3	0.181	0.11555	0.51148	-0.41	-23.41	0.51026	-6.78	2582
ALP 403	STS	3.6	19.5	0.185	0.11513	0.51146	-0.41	-23.80	0.51025	-7.09	2602
ALP 422	STS	12.2	69.8	0.175	0.11053	0.51145	-0.44	-23.99	0.51145	-6.34	2501
ALP 435	WTQ	1.0	5.0	0.200	0.11968	0.51157	-0.39	-21.65	0.51031	-5.87	2551
ALP 448	DTQ	2.3	12.1	0.190	0.12073	0.51146	-0.39	-23.80	0.51019	-8.24	2757

^a Assuming time (*t*) to be 1600 Ma, BGZ - biotite graphite zone, IF-VOB - Iron formation upper ore body, OEGQ - ore equivalent garnet quartzite.

quartzofeldspathic provenances than average shale (Lipson, 1990).

Sm-Nd Isotope Geochemistry

A full table of Sm-Nd isotope data including T_{CHUR} and T_{DM} model ages, as well as $\epsilon_{\text{Nd}(t)}$ values, is given in Table 5. Sm/Nd ratios vary between 0.17 and 0.20, in general, with higher ratios present in the garnet quartzite sample ALP 172g, the iron formation sample ALP 75 and a sample of Median Schist (ALP 125) from Maanhaarkop, which also has much higher $^{143}\text{Nd}/^{144}\text{Nd}$ ratios than the other metasediments. The Namies Schist, in general, has younger depleted mantle model ages (T_{DM}) compared to those of the Ore and Shaft Schist Formation metapelites and the regional rocks (Figure 7d; Table 5).

Based on the single zircon U-Pb ages obtained in this study (see later) a value of 1.6 Ga is taken as the age of deposition of the Bushmanland Group in order to determine $\epsilon_{\text{Nd}(t)}$ values. The metasediments have similar $f^{\text{Sm/Nd}}$ values, but show a range of $\epsilon_{\text{Nd}(t)}$ values (Figure 7b) denoting a degree of mixing in the metasediments (Bock *et al.*, 1994). The Namies Schist and White Quartzite have the highest $\epsilon_{\text{Nd}(t)}$ values suggesting derivation from a more depleted provenance, whereas the Shaft Schist has lower $\epsilon_{\text{Nd}(t)}$

values suggesting derivation from a more enriched, crustal-type provenance. Samples ALP 172g and ALP 125 plot away from this horizontal trend toward higher $f^{\text{Sm/Nd}}$ values and greater degrees of LREE depletion. The metasediments were derived from fractionated provenances, as denoted by low $f^{\text{Sm/Nd}}$ values.

The Sm-Nd model ages indicate that the Bushmanland Group metasediments have a provenance with mantle separation ages of ~2.5 to ~1.8 Ga (T_{CHUR}) or ~2.85 to ~2.25 Ga (T_{DM}) (Figure 7c and d; Table 5). The Namies Schist has younger T_{DM} model ages (~2.39 to ~2.25 Ga – Table 5) than the other metasediments, which generally have older T_{DM} model ages ranging between ~2.4 Ga and ~2.65 Ga and older. This reflects the younger zircon ages (Table 6; Figures 8a and 9) and differing chemistry of the Namies Schist compared to the other metapelitic schists or the quartzites. The regional metapelites and quartzites have older model ages than those at Aggeneys (Figures 7c and d).

Geochronology

Methodology

For the geochronological investigation, crushed samples of 1 to 2 kg were subjected to routine heavy mineral separation. The zircons were hand-picked, mounted in

Figure 7. Sm-Nd isotope systematics of the Bushmanland Group metasediments. (a) $\epsilon_{Nd}(t)$ vs. T_{DM} (after De Paolo *et al.*, 1991). (b) $f^{Sm/Nd}$ vs. $\epsilon_{Nd}(t)$. (c) T_{CHUR} histogram for the metasediments. (d) T_{DM} histogram.

epoxy and polished, prior to analysis using the Sensitive High Resolution Ion Microprobe (SHRIMP II), housed at the Research School of Earth Sciences at The Australian National University in Canberra. Details of SHRIMP analytical methods are given by Compston *et al.* (1984), Williams and Claesson (1987) and Williams (1998). The methodology used in this study is that given by Robb *et al.* (1999).

Metasedimentary lithologies from the Bushmanland Group were subjected to the geochronological investigation. Six metasediment samples and one amphibolite were selected to represent a section through the Bushmanland Group stratigraphy. All but two of the metasedimentary samples came from

borehole core through the Broken Hill Mine succession, with the amphibolite sampled from surface outcrop at Gamsberg and the Dark-type Quartzite from borehole core drilled at Namiesberg (Figure 2). Geochronological data tables can be found as supplemental data on the GeoScience World website at the following address: <http://sajg.geoscienceworld.org>.

The internal structure of the zircon grains was characterised using a scanning electron microscope to detect cathodoluminescent (CL) and backscattered electron (BSE) contrast. These images were collected at the Electron Microscopy Unit, the University of Cape Town, as well as at the Research School of Earth Sciences, the Australian National University.

Figure 8. Cathodoluminescent (CL) images of the detrital zircons showing analysed spots. **(a)** Namies Schist (ALP 39). **(b)** and **(c)** Dark Quartzite (ALP 42). **(d)** Ore Garnet Quartzite (ALP 114). **(e)** Shaft Schist (ALP 136). **(f)** Koeris Formation amphibolite (Gams-4).

Figure 9. U-Pb concordia diagram for zircons from Namies Schist (ALP 39) from the Broken Hill Mine, Aggeneys. The inset shows a histogram of $^{207}\text{Pb}/^{206}\text{Pb}$ ages for this sample.

Errors in the data tables and figures are at the 68% confidence level (1σ), with final weighted mean ages reported at the 95% confidence level. Decay constants used were 1.55125×10^{-10} (^{238}U) and 9.8485×10^{-10} (^{235}U). Statistical analysis and U-Pb Concordia diagrams were generated using Isoplot (Version 2.49) (Ludwig, 2001).

Namies Schist Formation

A sample of metapelitic Namies Schist (ALP 39) was sampled from borehole BH123 at the Broken Hill Mine (Figure 2). The zircons exhibit simple weak concentric zonation patterns of a uniform brightness (Figure 8a). Dark, unzoned rims are present in some grains, but these have not resorbed the concentrically zoned cores. Some dark cores that have been resorbed and overgrown by bright concentrically zoned overgrowths are present but are not common. Unzoned transgressive patches do not occur. Dark veins crosscut the zircons in places, but do not disrupt the zonation pattern.

The zircons show a limited age range with a unimodal distribution (Figure 9; Table A1). Rejecting results with greater than 10% discordancy that show large degrees of Pb-loss, and excluding a result with an age of 1391 ± 19 Ma (analysis 7.2, Table A1), which is significantly younger than the bulk of the detrital zircon ages, gives an age of 1732 ± 82 Ma (MSWD = 2.33, prob. = 0.86) ($n = 52$). Two analyses give concordant ages of ~ 1640 Ma (analyses 1.2 and 2.1, Table A1), which are the youngest detrital zircon ages in the Bushmanland Group at Aggeneys. A very limited number of grains have ages less than ~ 1.4 Ga (Figure 9) and with low Th/U ratios of less than 0.1 represent metamorphic overgrowths (Connolly, 2000) or analyses that overlapped onto

metamorphic overgrowths and rims. The restricted provenance age is also illustrated as a histogram in Figure 9.

Dark Quartzite of Broken Hill Quartzite Formation

Previous investigations of the zircons from a heavy mineral layer in the quartzite at Froneman se Kop to the east of the Broken Hill inselberg (Figure 2), described by Lipson *et al.* (1986) as sedimentary cross-bedding, produced a large range of highly discordant analyses (Armstrong *et al.*, 1988). No concordia intercept could be constructed, but geologically recent Pb-loss has caused a spread of data away from an ~ 2.0 to ~ 1.8 Ga grouping.

A sample of Dark Quartzite (ALP 42) from borehole BH123 at the Broken Hill Mine was taken for geochronological investigation in order to get better results for the age of the provenance to the quartzites than that obtained by Armstrong *et al.* (1988). The zircons are typically bright, weakly zoned to unzoned and of a uniform intensity (Figure 8b and c). Any dark cores that may be present have been resorbed and overgrown by bright, weakly zoned to unzoned overgrowths. Numerous grains contain large dark, unzoned overgrowths and rims, which have overgrown and resorbed the bright core areas (Figures 8b and c). These dark rims commonly result in euhedral grain shapes for the zircons. The dark unzoned rims are far more abundant, and of a greater volume than found within the Namies Schist sample described above.

The detrital zircons have a predominantly bimodal age distribution, with ages concentrated between ~ 2.15 and ~ 1.95 Ga, and between ~ 1.9 and ~ 1.75 Ga (Figure 10),

Figure 10. U-Pb concordia diagram for zircons from Dark Quartzite (sample ALP 42) from the Broken Hill Mine, Aggeneys. The inset shows a histogram of $^{207}\text{Pb}/^{206}\text{Pb}$ ages for this sample.

with geologically recent Pb-loss creating a degree of scatter in the concordia plot. The older grouping has an age of 2038 ± 41 Ma ($n = 16$, MSWD = 0.92), with the younger grouping having an age of 1786 ± 74 Ma ($n = 17$, MSWD = 0.80). The younger grouping is within error of the detrital zircons within the Namies Schist sample (ALP 39) described above.

Another grouping of between ~ 1.25 and ~ 1.0 Ga (Figure 10) is mostly of metamorphic overgrowths

(Table A2). Within this younger age grouping there are two sub-groupings, the first having an age of 1171 ± 31 Ma ($n = 5$, MSWD = 0.10). The second gives an age of 1040 ± 30 Ma ($n = 8$, MSWD = 0.14). Only one non-metamorphic grain (analysis 54.1), characterised by higher Th/U ratios typical of magmatic growth, gives a younger age of 1144 ± 73 Ma, outside the two main detrital age groupings. Older detrital zircons with ages older than ~ 2.2 Ga also occur, but are mostly highly

Figure 11. U-Pb concordia diagram for zircons from Dark-type Quartzite (sample ALP 427) from Namiesberg. The inset shows a histogram of $^{207}\text{Pb}/^{206}\text{Pb}$ ages for this sample.

Figure 12. U-Pb concordia diagrams for zircons from the Ore Schist Formation Garnet Quartzite (sample ALP 114) from the Broken Hill Mine, Aggeneys. (a) shows the older ages of the cores with (b) showing the younger ages of the low Th and Th/U overgrowths.

discordant (Figure 10). A single concordant age of 2872 ± 7 Ma is also recorded (analysis 9.1 – Figures 8b and 10; Table A2).

A quartzite sample (ALP 427), collected by Lipson (1990) from Namiesberg to the east of Aggeneys (Figure 2), and tentatively correlated with the Dark Quartzite, here termed the Dark-type Quartzite, was also analysed for U-Pb geochronology. This sample was analysed by U-Pb single zircon dating during the 1980s, and has been re-analysed for this study. Detrital zircon ages are presented as a histogram and a U-Pb concordia plot in Figure 11, while selected analytical data of the more concordant analyses are listed in Table A3. There is a predominant grouping with an age of 1805 ± 56 Ma

(MSWD = 1.41) ($n = 29$), and a smaller grouping with an age of 2020 ± 31 Ma (MSWD = 0.73) ($n = 12$). This age distribution is similar to, and within error of that from the Dark Quartzite described above. Some highly discordant outlier zircon ages of greater than ~2.5 Ga also occur.

Ore Schist Formation Garnet Quartzite

Zircons were extracted from a garnet quartzite associated with the sulphide-rich iron formations of the Lower Ore Body at the Broken Hill Mine (Figure 3). The garnet quartzite (sample ALP 114) directly underlies a mineralised amphibole magnetite iron formation. Zircons from this lithology are large and euhedral, with

Figure 13. U-Pb concordia diagram for zircons from the Shaft Schist (sample ALP 136) from the Broken Hill Mine, Aggeneys.

weakly zoned concentric zonation in dark overgrowths, which have overgrown and resorbed bright, weakly zoned cores (Figure 8d). The zoning is commonly totally disturbed as a result of blurring and disruption with some grains having dark unzoned rims. The dark weakly zoned overgrowths are characterised by high U and low Th contents and low Th/U ratios (Table A4). The bright zoned cores have low U, but relatively high Th contents.

The host rock is characterised by very low Th and U contents of 0.2 and 1.2 ppm respectively, with an exceptionally low Th/U ratio of 0.2.

On the U-Pb concordia plot (Figure 12), the bright cores of the zircons define a chord with an upper intercept of 2088 ± 38 Ma and a lower intercept of 994 ± 22 Ma. The bright cores have higher Th/U ratios and, in general, give older ages of ~ 2.0 Ga, representing

Figure 14. U-Pb concordia diagram for zircons from Koeris Formation amphibolite (sample Gams-4) from the Gamsberg inselberg.

detrital ages. The dark, low Th/U overgrowths (Figures 8d and 12), representing metamorphic overgrowths and rims, give a mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1018 ± 5 Ma (MSWD = 1.4).

Shaft Schist Formation

A sample of Shaft Schist (ALP 136) used in the geochronological investigation came from borehole BH164 drilled at the Broken Hill Mine, Aggeneys. Only a few zircons were separated from this metapelite, and were mostly small, being between 50 and 90 μm in size, and metamictised to varying degrees. The zircons are characterised by bright, generally unzoned cores, which have been resorbed and overgrown by darker unzoned overgrowths and rims (Figure 8e).

Dark overgrowths or rims have high U and low Th contents, and record younger ages of ~ 1.15 and ~ 1.03 Ga (Table A5). Bright unzoned cores have lower U and higher Th contents and have older ages. Most of the age data are very discordant, and seem to follow a discordia between an ~ 2.0 Ga source age and Pb-loss at ~ 1.03 Ga (Figure 13).

Koeris Formation Amphibolite

A sample of amphibolite from the Koeris Formation outcropping in the center of the basin-shaped Gamsberg inselberg, and with approximate co-ordinates $29^{\circ}14'40''\text{S}$ and $18^{\circ}57'30''\text{E}$ (Figure 2), yielded a few zircons that have been analysed. The Koeris Formation unconformably overlies the Shaft Schist (Lipson, 1990) or Gams Iron Formation (Rozendaal, 1986; McClung *et al.*, 2002) (Figure 3; Table 1) and cuts down into the Bushmanland Group to stratigraphic levels below that of the Namies Schist in some areas (McClung *et al.*, 2002). A sample of the amphibolite was taken from this lithology, as Reid *et al.* (1987) obtained a Sm-Nd isochron age of 1649 ± 90 Ma from this lithology. The age of extrusion of the parent basalt would thus provide a constraint on the minimum age of deposition of the Bushmanland Group.

The amphibolite is comprised predominantly of dark green hornblende, plagioclase (An_{28-45}), interstitial quartz and accessory amounts of cordierite, magnetite and orthoclase. Zircon is present in accessory amounts, and reaches sizes of 50 to 150 μm . The zircons are subhedral and are sector zoned with zones of a uniform brightness (Figure 8f). Primary zonation is not preserved, nor do dark unzoned transgressive patches occur.

These zircons have similar low Th/U chemistry as the garnet quartzite sample ALP 114 from the Broken Hill Mine and thus represent metamorphic zircon growth or recrystallisation. The Th and U contents of the zircons do not vary substantially (Table A6). The ages are also very similar (Figure 14) to those of the ore garnet quartzite from the Broken Hill Mine, giving an upper intercept age of 1016 ± 11 Ma (MSWD = 0.57, prob. = 0.89) and a mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1013 ± 9 Ma (MSWD = 0.63, prob. = 0.85).

Discussion

Geochemistry

Extensive winnowing, reworking and deposition of the Bushmanland Group in a passive margin setting (Figure 5c) is indicated by both the extreme silica purity and clean, sheet-like nature of the quartzites (Lipson, 1990), as well as elevated alumina concentrations in the Namies and Shaft Schists. In addition, trace element ratios, such as Zr/Th, Zr/Sc, Th/Sc, La/Th and La/Sc (Figure 5a), in excess of upper continental crustal values (Taylor and McLennan, 1985; McLennan *et al.*, 2006), also indicate extensive reworking. This is supported by the Early Proterozoic to Archaean depleted mantle model ages of the metasediments (Figures 7c and d; Table 5), as Sm-Nd model ages of passive margin samples tend to be much older than those from active margins indicating older, presumably recycled, crustal sources (McLennan *et al.*, 1990). Lipson (1990) and Hoffmann (1993) suggested that the extreme purity of the quartzites and the maturity of the metapelitic schists, along with a lack of a basaltic to andesitic provenance, argued for a cratonic interior provenance and deposition of the Bushmanland Group in a shallow siliciclastic sea environment with a constant rate of subsidence and / or provenance uplift, similar to that of the present-day Red Sea where active geothermal venting is depositing base metals in clayey muds accumulating in depressions on the sea floor (Bischoff, 1969).

The Namies Schist is more reworked and was derived from a more felsic feldspathic provenance than the Shaft or Shaft-type Schists due to the presence of positive Eu anomalies relative to NASC in these rocks (Figure 6c). It was deposited in an offshore shelf setting as shoreface sediments (Lipson, 1990). With relatively flat HREE patterns (Figure 6c) and low $(\text{Gd}/\text{Yb})_N$ ratios (Table 4), the Namies Schist and quartzites are likely to have been derived from K-rich granites (McLennan *et al.*, 1990). The Shaft Schist, with higher Cr and lower Zr contents than the Namies Schist, is more biotite- and clay-rich and was deposited as lagoonal or estuarine clay-rich black shales in a quiet, meromictic, anoxic reducing depositional environment (Lipson, 1990). This became less clay-rich higher up in the succession. Lipson (1990) argued that the Broken Hill Quartzite Formation represents the beach barrier, and the Ore Schist Formation largely represents a washover deposit comprising redistributed Namies Schist shoreface sediments. The smaller negative Eu anomaly (Figures 6b and c) of the Namies Schist compared to the Shaft Schist also suggests that it was derived from a less weathered source than the latter as samples lacking negative Eu anomalies show little or no signs of weathering, whereas those with prominent negative Eu anomalies are derived from severely weathered sources (Taylor *et al.*, 1986). Progradation and increasing degrees of reworking of the metasediments occurred toward the southeast (Lipson, 1990; Figure 4c), as seen in higher Al_2O_3 and TiO_2 contents in the regional Namies- and Shaft-type Schists compared to the Namies Schist (Table 2). The Ore Schist

Table 6. Summary of Sm-Nd and U-Pb single zircon SHRIMP ages for the Bushmanland Group of the Aggeneys District

Sm-Nd						
Lithology			T_{CHUR} (Ma)	T_{DM} (Ma)	Text figure	Table
Bushmanland Group metasediments			2485-1780	2840-2250	7	5
U-Pb single zircon SHRIMP ages						
Rock type	Sample Number	Inheritance T₀ (Ma)	M₂ T₁ (Ma)	M₃ T₂ (Ma)	Text figure	Table
Namies Schist	ALP 39	1732 ± 82			9	A1
Dark Quartzite	ALP 42	2038 ± 41	1171 ± 31	1040 ± 30	10	A2
		1786 ± 74				
Dark-type Quartzite	ALP 427	2020 ± 31			11	A3
		1805 ± 56				
Ore Garnet Quartzite	ALP 114	2088 ± 38		1017 ± 4	12	A4
Shaft Schist	ALP 136	~ 2000	1126 ± 27 ^a	~1030	13	A5
Amphibolite	Gams-4			1013 ± 9	14	A6

^aResult based on one analysis

Formation metapelites have a predominantly clastic-dominated quartzofeldspathic nature dominated by clays (Lacassie *et al.*, 2004), as seen by the positive correlation between TiO₂ and Al₂O₃ in these metapelites (Figure 4d). A progression from a more quartzofeldspathic, felsic-dominated provenance, denoted by low Sc and high Th/Sc ratios, to a more mafic-dominated provenance, with decrease in mineralogical maturity, occurs upwards in the stratigraphy (Figure 5b). The Namies Schist shows a progression from a less mature (or less reworked), Al₂O₃- and TiO₂-rich group with lower SiO₂ contents to a more reworked SiO₂-rich, Al₂O₃- and TiO₂-poor, quartzose fraction (Figure 4a and b) passing upwards into the White Quartzite, a feature also noted by Lacassie *et al.* (2006).

Geochronology

The Bushmanland Group metasediments predominantly record two detrital zircon age populations of ~2.12 to ~1.97 Ga and ~1.88 to ~1.64 Ga (Table 6). The presence of a few >2.6 Ga Archean grains may represent a very small Archean input, or be simply due to contamination

during zircon separation and dating. Possible provenances of Paleoproterozoic age outcropping to the north, northwest and west, the sediment transport direction for the Bushmanland Group (Lipson, 1990), include the Richtersveld Subprovince and the gneisses of the Gladkop Suite around Steinkopf (Figure 1).

Rocks of the Richtersveld Subprovince form a composite calc-alkaline igneous province subdivided into two major components, the older extrusive Orange River Group (Reid, 1977), comprised of mafic and felsic lavas of 1996 ± 15 Ma age (Reid, 1979b), and the younger Vioolsdrif Intrusive Suite (Reid, 1979a; 1982), comprised of tonalites, granodiorites, adamellites, leucogranites and quartz-feldspar porphyries, of 1996 ± 71 Ma age (Sm-Nd isochron – Reid, 1997). Previously unpublished U-Pb SHRIMP zircon data for the Richtersveld Subprovince is given in Table A7. The rhyolites of the Orange River Group give a U-Pb upper intercept age of 1935 ± 55 Ma and a lower intercept age of 895 ± 490 Ma (MSWD = 2.2). The large errors are due to a large amount of discordancy in the data. Younger ages of less than 1900 Ma are obtained for the intrusion of the Vioolsdrif Intrusive Suite, with a

Table 7. Summary of age data for the possible provenance areas to the Bushmanland Group in the Namaqua Province.

Lithology	Rb-Sr Age (Ma)	Sm-Nd age (Ma)	T_{CHUR} (Ma)	T_{DM} (Ma)	Th-Pb age (Ma)	Pb-Pb age (Ma)	U-Pb zircon age (Ma)
Orange River Group	1957 ± 54 ^a 1927 ± 905 ^d	2085 ± 89 ^d	1900 to 2123 ^c	2094 to 2293 ^c	1958 ± 61 ^a	2067 ± ⁸⁰ / ₈₆ ^a	1875 ^a 1996 ± 15 ^b 1935 ± 55 ^f
Orange River Group – rhyolites							
Vioolsdrif Intrusive Suite	1676 ± 42 ^d	1996 ± 71 ^c	1765 to 2010 ^c	2116 to 2238 ^c			
Vioolsdrif Intrusive Suite – tonalite	2014 ± 142 ^c						1883 ± 15 ^f
Vioolsdrif Intrusive Suite – granite					1973 ± 550 ^d	1839 ± 58 ^d	
Vioolsdrif Suite leucogranites							1870 to 1890 ^f
Gladkop Suite						1770 ± ⁺¹⁸⁴ / ₋₁₉₀ ^d	
1822 ± 36 ^e Brandewynsbank Gneiss	1824 ± 70 ^d						
Steinkopf Gneiss	1806 ± 102 ^d					1836 ± ⁺²⁰² / ₋₂₁₈ ^d	
Noenoemaasberg Gneiss							~2000 ^d

^a Reid (1979a); ^b Reid (1979b); ^c Reid (1997); ^d Barton (1983); ^e Robb *et al.* (1999); ^f reported in this study.

tonalite giving an upper intercept age of 1883 ± 15 Ma (MSWD = 1.8), and the leucogranites giving a similar spread of ages between ~ 1.89 and ~ 1.87 Ga. In general, the Richtersveld Subprovince predominantly gives ages of between ~ 1.92 and ~ 1.86 Ga (Table 6). Depleted mantle (T_{DM}) Sm-Nd model ages of ~ 2.29 to ~ 2.09 Ga for the Orange River Group and ~ 2.24 to ~ 2.12 Ga for the Vioolsdrif Intrusive Suite (Reid, 1997; Table 7) are similar to, and slightly younger than those of the Bushmanland Group metasediments (Figure 7d; Table 5).

The grey-pink orthogneisses of the Gladkop Suite (Van Aswegen, 1983), to the west of Aggeneys (Figure 1), with a Rb-Sr age of 1824 ± 70 Ma (Barton, 1983) and a U-Pb zircon age of 1822 ± 36 Ma (Robb *et al.*, 1999) (Table 7), may also have acted as provenance to the Bushmanland Group metasediments, as they have a similar age to the detrital zircon age population of the latter, as well as having appropriate compositions. Other provenance sources to the south, and possibly also to a far lesser extent to the east, may also have contributed detritus to the Bushmanland Group.

A break in sedimentation, marked by the unconformity recognised by McClung *et al.* (2002) at the base of the Broken Hill Quartzite Formation of the Kouboom Subgroup (the Dark Quartzite of Lipson, 1990; Figure 3; Table 1), is also recorded by not only changes in geochemical characteristics of the gneisses and quartzites, but also by detrital zircon ages and Sm-Nd model ages (Figure 7; Tables 5 and 6). The Namies Schist of the Wortel Subgroup has a younger single detrital zircon population and younger Sm-Nd model ages than the metasediments of the overlying Kouboom Subgroup. The older ~ 2.0 Ga age population was not sourced prior to the erosional hiatus (Table 6), but begins to dominate upwards in the Kouboom Subgroup.

Work by Reid *et al.* (1987) led them to suggest an age of sediment deposition of between ~ 2.0 and ~ 1.65 Ga. The detrital zircon ages obtained in this study, however, suggest a younger depositional age for the Bushmanland Group. No major tectonic, magmatic or metamorphic events appear to have been recorded between ~ 1.64 Ga (the age of the youngest detrital zircon in the Namies Schist, analysis 2.1, Table A1) and ~ 1.2 Ga so that this period is a likely time for deposition of the Bushmanland Group and associated mineralisation at Aggeneys (Figure 15). Raith *et al.* (2003) reported ages for detrital zircons from the tectono-stratigraphic lowermost part of the Kamiesberg Subgroup around the Bitterfontein area in the southwestern Namaqua Province of between ~ 1.25 and ~ 1.2 Ga and an age of deposition prior to a tectonothermal event at ~ 1.19 Ga. Thus an age of deposition of ~ 1.2 Ga for the Bushmanland Group is also feasible.

The Aggeneys – Gamsberg BHT deposits differ from typical BHT deposits in that, based on the detrital zircon ages obtained in this study, they are younger than other BHT deposits, such as the Broken Hill Main Lode, New South Wales, Cannington, Queensland, Australia and the

Zinkgruvan deposit in Sweden, all of which are of Paleoproterozoic age (Parr and Plimer, 1993; Walters, 1996). The Bushmanland Group deposits also seemingly differ from other BHT deposits (Parr and Plimer, 1993; Walters, 1996) in having clean, highly mature quartzites, a passive margin setting and the absence of evaporitic lithologies in the near ore and footwall sequences.

The voluminous pink and grey granitic gneisses, including the Achab and Hoogoor Gneisses, which occur throughout the region (Figure 1) and act as present day basement to the supracrustal succession, have been cited as provenance, basement and possible source of base metals to the metasediments by previous workers (Duncan *et al.*, 1984, 1985; Moore *et al.*, 1990; Reid *et al.*, 1997b). However, these gneisses are dominated by ~ 1.21 to ~ 1.17 Ga magmatic zircon U-Pb ages (Bailie *et al.*, 2005). No detrital zircons of this age are recorded in the Bushmanland Group (Table 6), so that these granitic gneisses could not have acted as provenance, basement or source of base metals to the Bushmanland Group metasedimentary succession, but are rather intrusive into the supracrustal succession.

The Bushmanland Group metasediments at Aggeneys show similar parageneses, detrital zircon and Sm-Nd model age distributions to that of the Khurisberg Subgroup of the Okiep District (Clifford *et al.*, 1981; 2004; Figure 15), a possible correlative of the Bushmanland Group in the Aggeneys area (Clifford *et al.*, 1981; Joubert, 1986). Barton (1983) and Robb *et al.* (1999) have argued, however, that the Khurisberg Subgroup pre-dates the intrusion of the *ca.* 1820 Ma old granitic rocks of the Gladkop Suite. As such, the granitic rocks of the Gladkop Suite, occurring in the eastern part of the Ratelpoort Synform north of Springbok (Figure 1), still need to be accurately dated in order to firmly establish a minimum age for the Khurisberg Subgroup (Clifford *et al.*, 2004).

The detrital zircons of the Bushmanland Group in the Aggeneys District have been subjected to two discrete periods of new metamorphic zircon growth, present as low Th/U overgrowths and rims. Metamorphic growth may be distinguished from magmatic growth in zircons by high U and low Th contents, low Th/U ratios, and diffuse weakly zoned areas or dark unzoned patches, rims, overgrowths and embayments (Connelly, 2000).

The Kibaran Orogeny (~ 1.22 to ~ 1.17 Ga) represents a major tectono-thermal event, corresponding to the collision of the Namaqua Province with the Kaapvaal Craton (Hartnady *et al.*, 1985; Thomas *et al.*, 1993a; Jacobs *et al.*, 1993; Jacobs and Thomas, 1994). In the Aggeneys District this episode was dominated by magmatism due to extensive crustal reworking, partial melting and granitic magmatism in the form of the Aggeneys Granite Suite (Bailie *et al.*, 2005), accompanied by the regionally significant D_2 deformation and peak upper amphibolite facies grade M_2 metamorphism which correlates with a similar period

Figure 15. Comparison of geochronology for Bushmanland Group metasediments of the Aggeneys District and the metasediments of the Khuriberg Subgroup, Okiep District, Namaqualand to the west (from data in Clifford *et al.*, 2004).

of extensive magmatism and amphibolite facies metamorphism in the Okiep District in Namaqualand to the west (Robb *et al.*, 1999; Clifford *et al.*, 2004; Figure 15) and deposition of the Kamiesberg Subgroup in the southern Namaqua Province (Raith *et al.*, 2003). A similar period of tectono-magmatism occurred in the Natal Province in the east (McCourt *et al.*, 2006; Eglington, 2006). This episode is not extensively recorded as metamorphic overgrowths or rims in the metasediments, with only the Dark Quartzite (ALP 42; Figure 10; Tables 6 and A2) having numerous low Th/U overgrowths and rims of 1171 ± 31 Ma age. This age corresponds well with a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1175 ± 23 Ma for this tectono-magmatic episode for zircons from a cordierite-hypersthene paragneiss from the Okiep District (Clifford *et al.*, 2004). Kibaran Orogeny metamorphism and deformation caused remobilisation and recrystallisation of the Aggeneys

massive sulphide ores (Joubert, 1986), such as into the hinge zones of F_2 folds. By ~ 1.17 Ga M_2 metamorphism started waning and a period of tectonic quiescence started.

Subsequently, after a period of ~ 140 Ma of tectonic quiescence, tectonism, magmatism and metamorphism accompanied deformation during the Namaquan Orogeny (~ 1.06 to ~ 1.01 Ga), particularly to the west in Namaqualand in the Okiep District (Robb *et al.*, 1999; Clifford *et al.*, 2004; Andreoli *et al.*, 2006; Eglington, 2006) (Figure 15). There is no evidence to suggest a magmatic or metamorphic event in the Aggeneys District between ~ 1.17 and ~ 1.04 Ga. Similar periods of crustal growth and metamorphism of between ~ 1.21 and ~ 1.16 Ga and ~ 1.07 and ~ 1.03 Ga are recorded by Thomas *et al.* (1993b; c), Eglington (2006) and McCourt *et al.* (2006) for granites and granitic gneisses in the Natal Province on the east coast of South Africa.

No magmatism is recorded in the Aggeneys District during the Namaquan Orogeny. Rather this area was affected by deformation (D_3) and metamorphism (M_3), as recorded by dark, unzoned overgrowths and rims on detrital zircons having low Th/U ratios (Table 6). Extensive fluid flow along lithological contacts (e.g. sample ALP 114) may have occurred at this time. M_3 metamorphism in the Aggeneys District occurred at ~1.02 to 1.01 Ga, the age of low Th/U metamorphic overgrowths in zircons from the ore garnet quartzite (Figure 12; Table A4) and Koeris Formation amphibolite (Figure 14; Table A6). The lowermost Wortel Subgroup of the Bushmanland Group shows minimal effects of Namaquan Orogeny metamorphism.

The Kalahari-Grunehogna Craton could have lain to the southwest of Laurentia with the Namaqua-Natal Belt facing outboard and away from the Laurentian Craton (Powell *et al.*, 2001). Pisarevsky *et al.* (2003) suggest that the Kalahari Craton could have lain off the western margin of Australia until ~800 to ~750 Ma. These authors proposed that the Kalahari-Dronning Maud Land Craton joined the Australia-Mawson Craton during oblique collision between ~1.1 and ~1.0 Ga. Metamorphism in both Dronning Maud Land and the Darling Mobile Belt occurred at ~1.08 to ~1.05 Ga (Jacobs *et al.*, 1998) and metasediments in both belts have indistinguishable detrital zircon populations (Pisarevsky *et al.*, 2003 and references therein). Pisarevsky *et al.* (2003) also noted that, with this model, paleopoles from the Kalahari Craton converge with the Laurentian apparent polar wander path (APWP) between ~1.07 and ~1.0 Ga. The collision of the Bushmanland Subprovince, with the co-joined Richtersveld Subprovince, with the Kakamas Terrane at ~1.2 Ga, which caused upper amphibolite M_2 metamorphism, thus forms a precursor to the amalgamation of the Kalahari-Dronning Maud Land Craton with the Australia-Mawson Craton during Mesoproterozoic times. The subsequent metamorphism at ~1.04 to ~1.01 Ga, which was accompanied by granulite grade metamorphism in the Okiep District in Namaqualand to the west, was associated with convergence and collision of the Kalahari Craton with Laurentia during Rodinia construction.

Summary

The Bushmanland Group metasediments in the Aggeneys District were derived from old upper continental crust, likely to have been a moderately weathered provenance comprised of granodiorites, tonalites and granites, and their extrusive equivalents. Mixed sources are likely from the geochemical signatures of the metasediments. The metapelitic schists were derived from illite- and smectite-bearing mudstones that had not advanced to the kaolinite stage (Lipson, 1990; Hoffmann, 1993; Figure 4e). A degree of extensive winnowing and reworking of the sediments also likely occurred prior to, or just after deposition (Figure 5a), suggesting a cratonic interior provenance with a passive margin setting. All the metasediments exhibit

K-enrichment and Na-depletion relative to average shale or arkose compositions (Figure 4f).

The fundamental chemical and mineralogical differences between the basal Namies and upper Shaft Schists may have resulted from erosion of different provenances (Lipson, 1990), where a difference in detrital zircon ages and Sm-Nd model ages is also noted between the two (Table 6). The Namies Schist, with a greater feldspathic character and compositional range, was derived from a slightly more quartzofeldspathic provenance than the Shaft Schist, which was, in turn derived from a more plagioclase- and quartz-poor provenance and had a clay-dominated precursor. An increasingly greater mafic component to the provenance is present with height in the stratigraphy.

Detrital zircons in the Bushmanland Group predominantly record two age populations of ~2.12 to ~1.97 Ga and ~1.88 to ~1.64 Ga (Table 6), so that at least two distinct provenances fed the Bushmanland Group basin in this area. The metasediments of the older Wortel Subgroup predominantly sourced the younger provenance, whereas the overlying Kouboom Subgroup sourced both. Depleted mantle (T_{DM}) Sm-Nd model ages of ~2.85 to ~2.25 Ga (Figure 7e; Tables 5 and 6) reflect derivation from old, recycled crustal sources. Possible provenances include the ~2.1 to ~1.85 Ga magmatic rocks of the Richtersveld Subprovince to the northwest (Reid, 1977; 1979a; b, 1982; 1997) (Tables 6 and A7), as well as the granitic orthogneisses of the Gladkop Suite (Van Aswegen, 1983), to the west of the Aggeneys District (Figure 1), having ~1.84 to ~1.82 Ga ages. Other possible provenances may have been to the south as well as to the north and east. Bushmanland Group deposition is taken to have occurred between ~1.64 Ga (the youngest detrital zircon) and ~1.21 Ga, the onset of the Kibaran Orogeny in the Aggeneys District (Figure 15), making it younger than other BHT deposits. The Bushmanland Group shows a similar age distribution of detrital zircons and Sm-Nd model ages as the Khurisberg Subgroup in the Okiep District to the west (Clifford *et al.*, 2004) (Figure 15), with which it may possibly be correlated.

The tectono-magmatic Kibaran Orogeny (~1.21 to ~1.17 Ga), which is marked by extensive magmatism (the Little Namaqualand Suite), peak D_2 deformation and M_2 upper amphibolite facies grade metamorphism, is not preferentially recorded as metamorphic overgrowths and rims in the Bushmanland Group metasediments. The timing of M_2 metamorphism in the Aggeneys District is taken as ~1.17 Ga from metamorphic overgrowths on a Dark Quartzite sample. The ~1.04 to ~1.01 Ga Namaquan Orogeny, marked by M_3 metamorphism and D_3 deformation, is recorded by metamorphic overgrowths and rims on detrital zircons of predominantly ~1.02 to 1.01 Ga ages.

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