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Rb-Sr and Sm-Nd systematics of granitic and metamorphic rocks in the Namaqualand Metamorphic Complex, South Africa: Implications for evolution of marginal part of Kaapvaal craton

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Abstract: We analyzed Sr and Nd isotopic compositions of granitic and metamorphic rocks from the Namaqualand area, South Africa. The Concordia Granite, a member of the Spektakel Suite, near Garies, has a Rb-Sr whole rock isochron age of 1017±30 Ma with an initial Sr isotopic ratio of 0.7110±0.0029. This age coincides with the SHRIMP U-Pb zircon age reported from the Okiep Copper District (OCD) within an error. Sm-Nd model ages of this granite (T_{CHUR} : 1030–1195 Ma, T_{DM} : 1579–1710 Ma) are younger than those in the OCD. The Nababeep Granite Gneiss can be divided into two groups, High and Low NdI Groups, in the Sm-Nd system. The former gives a Rb-Sr whole rock isochron age of 1131±62 Ma, and the latter indicates a Rb-Sr isochron age of 1246±62 Ma. The gneisses of the High NdI Group are distributed in the southern part of the study area. On the other hand, the Low NdI Group are mainly distributed in the northern area. The boundary between the two parts accords closely with the boundary between lower and upper granulite-facies, which suggests that the Nd isotopic compositions of source rocks of these gneisses were not uniform, and that there is a gap between northern and southern areas. This affects the Nd isotopic composition of the latter granitic rocks such as the Concordia Granite.

key words: South Africa, Namaqualand, Concordia Granite, Nababeep Granite Gneiss, Sr and Nd isotopic compositions, Rb-Sr and Sm-Nd whole rock isochron ages

1. Introduction

The Namaqua–Natal Metamorphic Province (NNMP) is an east to east-southeasterly trending belt of poly-deformed and metamorphosed Paleozoic to Mesoproterozoic rocks extending around the southern and southwestern margins of the Kaapvaal Craton of South Africa (Fig. 1). This Province connects with Dronning Maud Land in Antarctica and the Grenville Province of North America. The NNMP is believed to have formed as part of an extensive network of 1300–950 Ma mobile belts during consolidation of the Rodinia supercontinent (Hoffman, 1991), which have been collectively referred to as products of the Kibaran tectonometamorphic cycle (Thomas *et al.*, 1994). To the south and west, the NNMP was been reworked during the Neoproterozoic to Paleozoic (Pan-

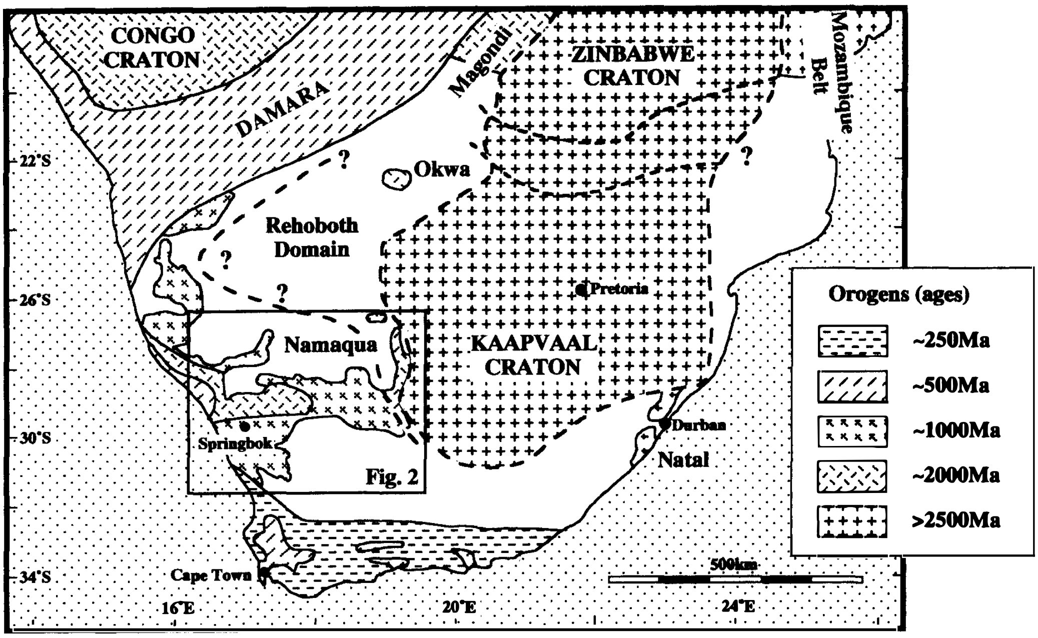

Fig. 1. Location and regional tectonic setting of the Namaqua–Natal Province in southern Africa and its relationship to pre-existing Eburnian and Archaean cratonic blocks (modified after Thomas et al., 1994).

African) Saladanian and Gariep events. The central parts of the NNMP are concealed beneath younger Phanerozoic supracrustal material. Therefore, exposure of metamorphic and intrusive rocks in the present day erosional surface is limited to the eastern Natal belt and western Namaqua belt. The study of metamorphism and igneous activity in Namaqualand aids elucidation of regional tectonism in the Grenville and Pan-African periods. The Namaqualand Metamorphic Complex consists of various granitoid intrusive suites, with lesser amounts of metasedimentary and metavolcanic rocks. Thus, the evaluation of the origin and mechanism of emplacement is important in understanding the evolution of this complex.

The Okiep Copper District (OCD) (Fig. 2) is the oldest formally-proclaimed mining district in southern Africa, with many copper mines. Numerous geological, petrological, mineralogical and structural reports and chronological data have been presented for the OCD. In contrast, there are few reports from the southern part of the mining district, and isotopical data are particularly sparse.

In this paper we present Rb-Sr age, and Sm and Nd data from granitic and metamorphic rocks in the area between Springbok and Garies, and discuss timing of igneous activity in this area and source materials of igneous rocks.

2. Geological outline

As illustrated in Fig. 2, the Namaqua belt has been subdivided on structural and lithological grounds into a number of tectonostratigraphic terranes (*e.g.* Hartnady *et al.*, 1985; Thomas *et al.*, 1994). The rocks of Bushmanland (central and western Namaqualand) are structurally and stratigraphically distinct from those of eastern

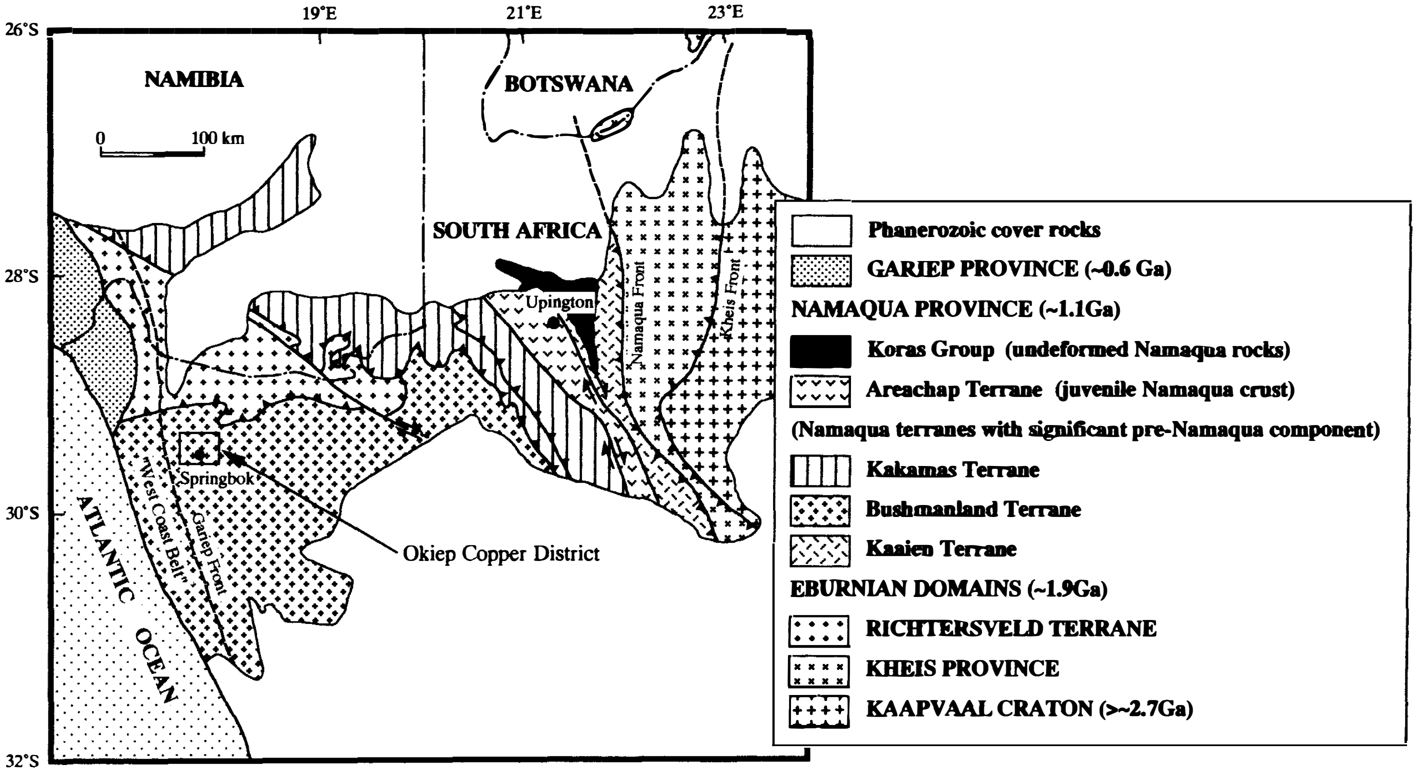

Fig. 2. Tectonic subdivisions of the Namaqua sector, modified after Thomas et al. (1994).

Age (Ma)	Rock-forming events	Deformational events	Metamorphic events
500 ~ 550		Post-Nama open folding and faulting	Lower greenschist facies
550 ~ 650	Deposition of the Nama Group		
717 ± 17	Intrusion of mafic dykes		
(800 ~ 850)	Long period of denudation and cooling		
950 ~ 1000	Emplacement of pegmatite	North-south compression	Amphibolite facies
1022 ~ 1057	Intrusion of Koperberg Suite	Steep structures	
1058 ~ 1105	Intrusion of Spektakel Suite Kweekfontein Granite Rietberg Granite (1058Ma) Concordia Granite (1064Ma)	Major open folds Regional recumbent folds	Granulite facies
1179 ~ 1223	Intrusion of Little Namaqualand Suite Modderfontein Granite Gneiss (1199Ma) Nababeep Granite Gneiss (1214, 1223Ma)	Intrafolial folds	
1822 ~ 1824	Intrusion of Gladkop Suite Neonoemaaberg Granite Gneiss Brandewynsbank Granite Gneiss (1822, 1824Ma)		

Fig. 3. Sequence of events in the Okiep Copper district (based on Clifford et al., 1995; Raith and Harley, 1998).

Namaqualand (Kakamas, Areachap and Kaaien Terranes). The metasedimentary and metavolcanic rocks in the Bushmanland Terrane are composed mainly of quartzites and pelites, with minor intercalations of Al-Si enriched and Mg-rich rocks, quartz conglomerates, banded iron formations and calc-silicate rocks. The rocks of this terrane display peak metamorphic grades ranging from upper amphibolite facies north of the OCD and in the extreme south, to upper granulite facies in an east-trending belt around Garies and Kliprand (Albat, 1984).

The intrusive rocks in the Bushmanland Terrane are divided into four suites (Lombaard *et al.*, 1986) (Fig. 3). Two suites of metamorphosed intrusive rocks, the Gladkop Suite and the Little Namaqualand Suite, clearly predate the main metamorphic event. The Spektakel and the Koperberg Suites clearly postdate emplacement of the Little Namaqualand Suite. The Gladkop Suite mainly consists of strongly deformed granitoids. Their formation has been attributed to continental accretion during the Eburnian orogeny. The Little Namaqualand Suite is composed of mesocratic quartz-feldspar-biotite-augen gneisses and megacrystic gneisses, and is subdivided into the Nababeep and Modderfontein Granite Gneisses. Field relations indicate that the Nababeep Granite Gneiss was intruded by the Modderfontein Granite Gneiss (*e.g.* Raith, 1995). Whole rock Rb-Sr ages of 1179 Ma (Barton, 1983) and 1223 Ma (Clifford *et al.*, 1995) were obtained for this suite, and were interpreted as the age of the onset of the granulite facies metamorphism. U-Pb zircon ages of 1212 Ma (Robb *et al.*, 1999) for the Nababeep Granite Gneiss and 1199 Ma (Robb *et al.*, 1999) for the Modderfontein Granite Gneiss are considered as the age of emplacement. The gneisses of this suite have been described as early to syn-orogenic granitoids formed by anatexis and reworking of older

Proterozoic crust. The Spektakel Suite consists of the Concordia, Rietberg and Kweekfontein Granites. This suite is largely a massive type, containing K-feldspar megacrystic granitoids. The Rietberg Granite intrudes and overlies the Concordia Granite; however, the contact between the two Granites is gradational (Lombaard *et al.*, 1986). U-Pb zircon ages of 1064 and 1058 Ma (Robb *et al.*, 1999) were obtained for the Concordia Granite and the Rietberg Granite, respectively. Clifford *et al.* (1995) reported whole rock Rb-Sr age of 1105 Ma without separating both granites. These ages are interpreted as ages of emplacement. However, Gibson *et al.* (1996) regarded the Rb-Sr whole rock isochron shown by Clifford *et al.* (1995) as errorchron. Ultramafic to intermediate plutonic rocks of the Koperberg Suite preferentially intruded along subvertical East-West orientated zones of high strain, and are collectively known as the 'steep structure'. The whole rock Sm-Nd age of 1022 Ma (Clifford *et al.*, 1995) and U-Pb zircon ages of 1057 to 1037 Ma (Robb *et al.*, 1999) and 1029 Ma (Clifford *et al.*, 1995) were obtained for this suite. These rocks are unconformably overlain by sediments of the late Precambrian to the early Paleozoic Nama Group.

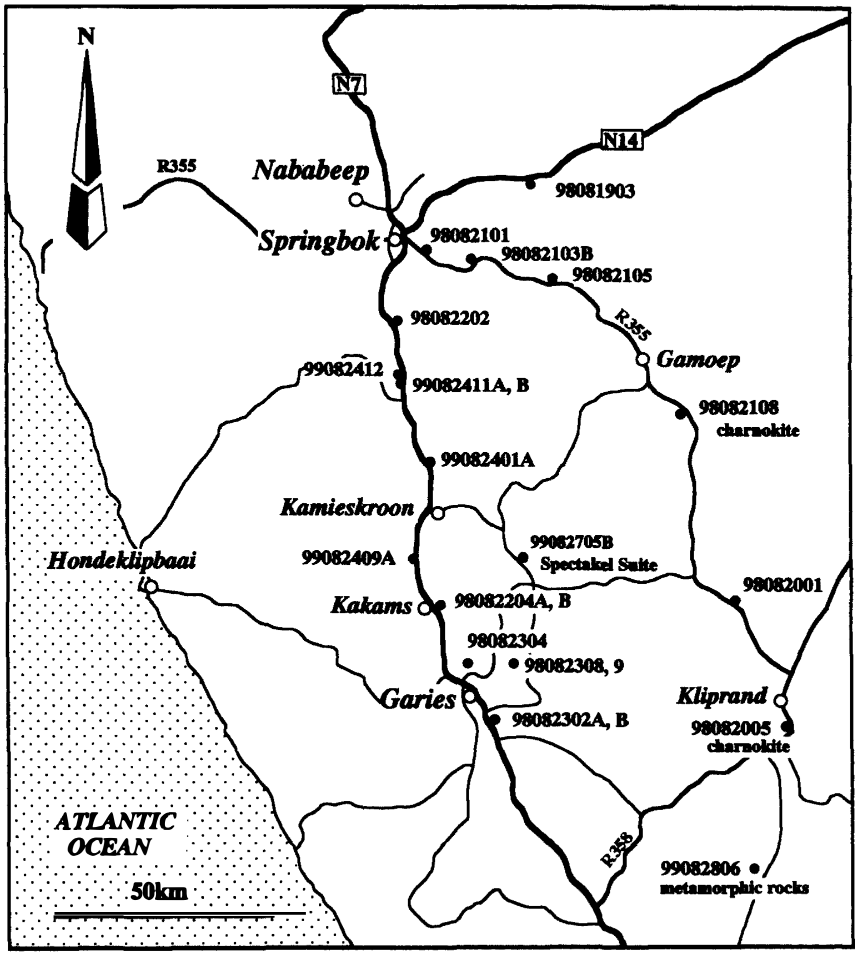

Fig. 4. Sampling points in the Nababeep Granite Gneiss and metamorphic rocks.

3. Samples and analytical procedures

We collected samples of Nababeep Granite Gneiss from the area between Springbok and Garies (Fig. 4). Metasedimentary rocks were collected from the outcrop shown by Nowicki *et al.* (1995). Charnokites were collected from two outcrops (Fig. 4). The Nababeep Granite Gneiss is a prominent member of the Little Namaqualand Suite. It is a mesocratic quartz-microcline-biotite-augen gneiss including minor mafic granulites. All rock types of this suite exhibit intense penetrative deformation and syn-kinematic metamorphic recrystallization.

We collected the Concordia granite from the masses near Garies (Fig. 5) and near Springbok (Fig. 4). One sample is a dyke, which intruded the Nababeep Granite Gneiss. We collected one sample of the Spektakel Suite from the area southeast of Kamieskroon too (Fig. 4), but could not decide which Granite it belongs to. The Concordia Granite is a

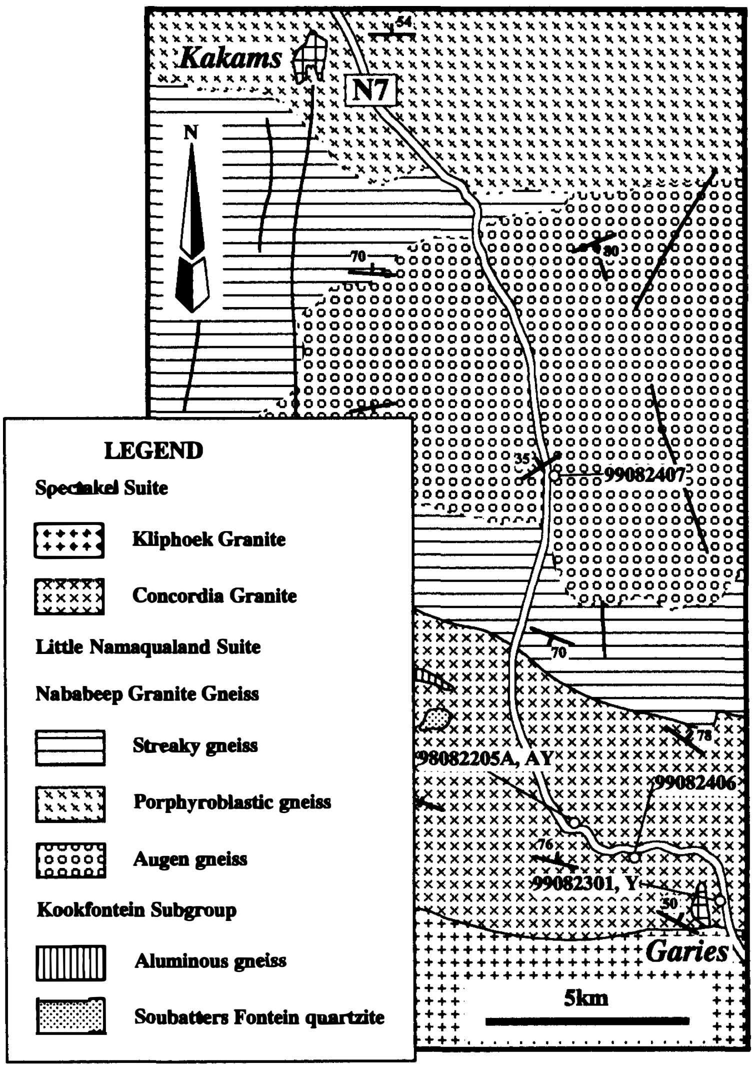

Fig. 5. Simplified geological map of the area from Garies to Kakamas, and sampling points in the Concordia Granite (modified after Jack, 1980).

Table 1. Rb, Sr, Sm and Nd concentrations of SARM-1 and 48 determined by isotopic dilution.

Sample No.	Rb(ppm)	Sr(ppm)	$^{87}Rb/^{86}Sr$	Sm(ppm)	Nd(ppm)	$^{147}Sm/^{144}Nd$
SARM-1	331.0	9.060	106.45	14.97	73.63	0.12295
(1/3)	332.1	9.059	107.01	15.10	74.58	0.12243
	331.7	9.005	107.53	14.99	73.81	0.12277
Average	331.6	9.041	107.00	15.02	74.01	0.12272
S.D.	0.56	0.031	0.54	0.070	0.50	0.00026
R.E.(%)	0.17	0.35	0.50	0.47	0.68	0.22
R.V.	325	10		15.8	72	
SARM-48	293.6	31.32	28.761	44.95	295.4	0.091972
(48/23)	293.7	31.32	28.770	44.34	287.5	0.093208
	294.7	31.99	28.264	44.30	289.1	0.092603
Average	294.0	31.54	28.598	44.53	290.7	0.092594
S.D.	0.61	0.39	0.29	0.36	4.2	0.000618
R.E.(%)	0.21	1.2	1.0	0.82	1.4	0.67
R.V.	291	29		47.2	307	

( ) : split / position number, R.V. : recommended value of Potts *et al* . (1992).
S.D. : standard deviation, R.E. : relative error.

medium to coarse grained leucogranite, with a granular to porphyritic texture and weak foliation. The Concordia Granite samples are classified as alkali feldspar granite to syenogranite. Alkali feldspar, plagioclase and quartz are major mineral constituents, and biotite and garnet are minor minerals.

Major and trace element concentrations of whole rock samples were determined with XRF at Niigata University and at the National Institute of Polar Research, by the methods of Takahashi and Shuto(1 997), Motoyoshi and Shiraishi(1 995) and Motoyoshi *et al.* (1996).

Isotopic analyses were performed on a MAT261-type (modified from MAT260) equipped with five Faraday cups and MAT262-type mass spectrometers with nine cups at Niigata University. The $^{87}Sr/^{86}Sr$ ratios and $^{143}Nd/^{144}Nd$ ratios were normalized to $^{86}Sr/^{88}Sr=0.1194$ and $^{146}Nd/^{144}Nd=0.7219$, respectively. Measured $^{87}Sr/^{86}Sr$ ratios were corrected relative to $^{87}Sr/^{86}Sr=0.710241$ for NBS-987. Measured $^{143}Nd/^{144}Nd$ ratios were corrected relative to $^{143}Nd/^{144}Nd=0.512784$ for JB-1a (reference sample of Geological Survey of Japan). The Nd isotopic ratio of JB-1a corresponds to $^{143}Nd/^{144}Nd=0.512638$ of BCR-1 (Kagami *et al.*, 1989). Sm, Nd, Rb and Sr concentrations were determined by isotope dilution using ^{87}Rb-^{84}Sr and ^{149}Sm-^{150}Nd mixed spikes. Rb-Sr and Sm-Nd isochron ages and initial Sr and Nd isotope ratios were calculated by the computer program of Kawano (1994) using the equation of York (1966) and the decay constants; $\lambda^{87}Rb=1.42\times10^{-11}/y$ (Steiger and Jäger, 1977), $\lambda^{147}Sm=6.54\times10^{-12}/y$ (Lugmair and Marti, 1978). Estimated errors for $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ ratios were 0.5% (1σ) and 0.01% (1σ), and those for $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ ratios were 0.1% (1σ) and 0.05% (1σ). Detailed isotopic analytical procedures are reported by Miyazaki and Shuto (1998), Hamamoto *et al.* (2000) and Yuhara *et al.* (2000).

Results of the isotopic analysis of reference samples, SARM-1 and -48, issued by the South African Bureau of Standards, are shown in Table 1. Measured $^{143}Nd/^{144}Nd$ ratios of SARM-1 and 48 are 0.511352±0.000016 ($2\sigma_m$; N=4) and 0.510993±0.000015 (N=3), respectively. Rb, Sr, Sm, Nd concentrations are in close agreement with the recommended values of Potts *et al.* (1992).

4. Results

4.1. Concordia Granite

The SiO_2 content of Concordia Granite near Garies ranges from 69.4 wt% to 71.6 wt% (Table 2). The sample with 75.9 wt% SiO_2 is Concordia Granite collected from the

Table 2. Whole rock chemical compositions of the Concordia Granite.

	Concordia Granite near Garies						Spektakel Suite	Concordia Granite*
Sample No.	99082406	98082301	99082407	98082205A	98082205AY	98082301Y	99082705B	98082101
SiO2(wt%)	69.36	70.61	70.63	71.21	71.46	71.61	68.21	75.94
TiO2	0.62	0.40	0.46	0.49	0.48	0.38	0.90	0.50
Al2O3	13.85	14.33	14.05	13.73	13.93	13.84	12.92	11.17
FeO*	3.47	2.46	2.59	2.66	2.43	2.28	4.93	2.66
MnO	0.03	0.03	0.02	0.05	0.04	0.02	0.04	0.05
MgO	0.61	0.58	0.65	0.68	0.69	0.56	1.89	0.55
CaO	1.57	1.52	1.50	1.69	1.70	1.55	1.98	1.41
Na2O	2.17	2.69	2.90	2.77	2.84	2.61	2.63	2.03
K2O	6.27	6.30	5.73	5.28	5.38	5.71	4.18	4.84
P2O5	0.21	0.08	0.16	0.12	0.12	0.12	0.06	0.05
L.O.I.	0.64	0.84	0.38	0.33	0.32	0.81	0.56	0.31
Total	98.80	99.84	99.07	99.01	99.39	99.49	98.30	99.51
Ba(ppm)	636	632	792	663	691	554	1196	471
Co	-	6	-	-	-	-	-	9
Cr	4	131	8	10	9	7	71	227
Cu	-	13	-	-	-	-	-	8
Nb	18	8	16	17	16	7	10	22
Ni	n.d.	73	n.d.	4	4	n.d.	29	113
Rb	350	332	265	392	403	313	216	292
Sr	102	157	174	129	132	151	299	63.3
V	19	20	22	28	28	18	81	23
Y	67	21	44	47	44	25	13	63
Zn	-	72	-	-	-	-	-	45
Zr	543	270	354	294	186	267	257	294

L.O.I. : Loss on ignition, n.d. : not detected.
*near Springbok

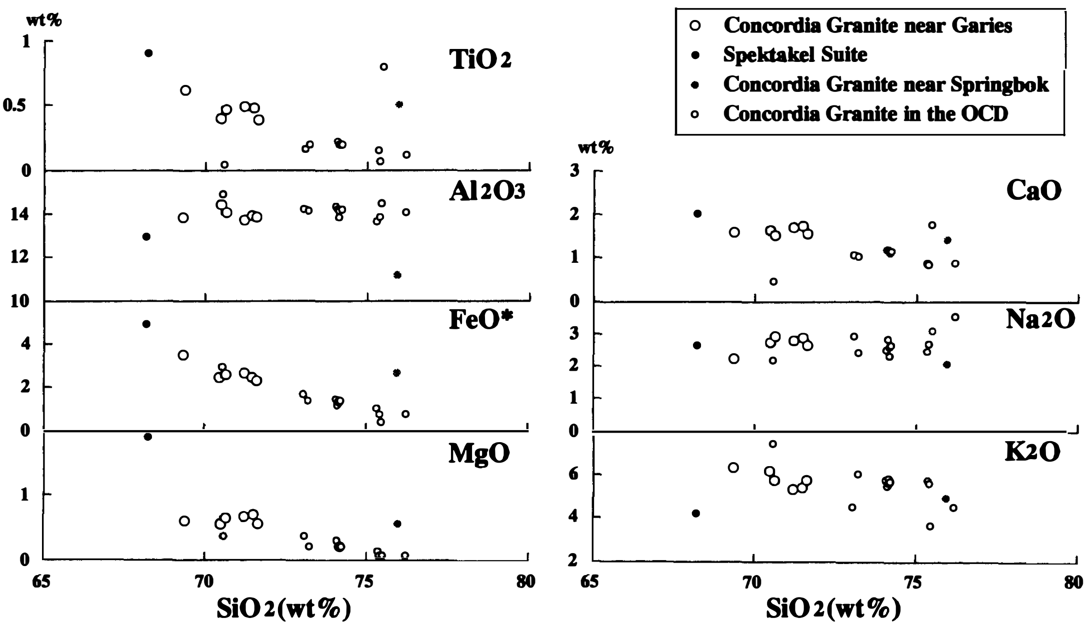

Fig. 6. SiO_2–oxide diagram of the Concordia Granite.

Springbok area. The sample from the Spektakel Suite has 68.2 wt% SiO_2 content. The major and trace element variations is illustrated in Harker diagrams (Figs. 6, 7). Major and trace element contents reported by Clifford *et al.* (1975), Raith (1995) and Brandriss and Cawthorn (1996) are plotted in the same diagrams. The Concordia Granite near Garies has lower SiO_2 content than that in the OCD. TiO_2, total Fe and K_2O contents of the Concordia Granite near Garies are negatively correlated with SiO_2, while Al_2O_3,

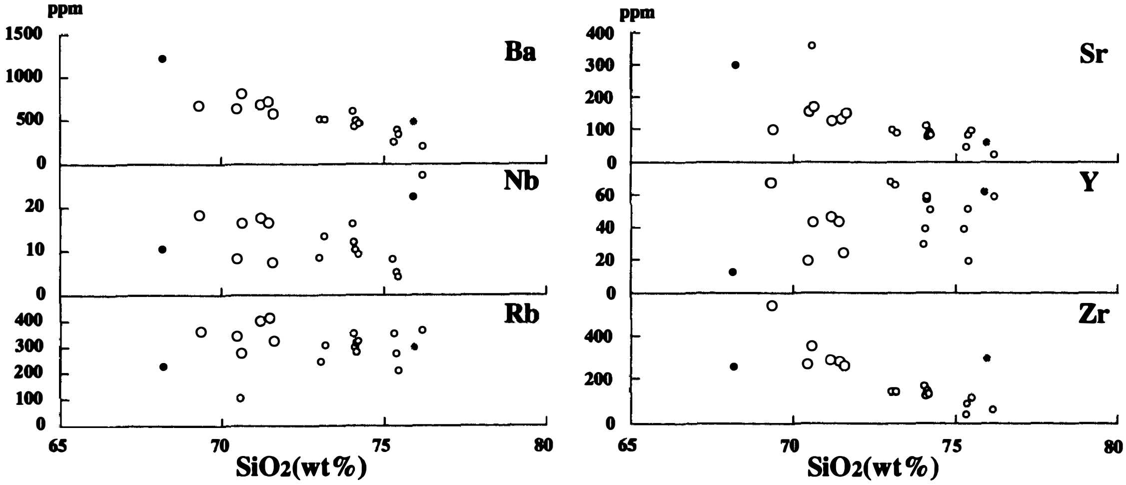

Fig. 7. SiO_2–trace element diagram of the Concordia Granite. Symbols are the same as those in Fig. 6.

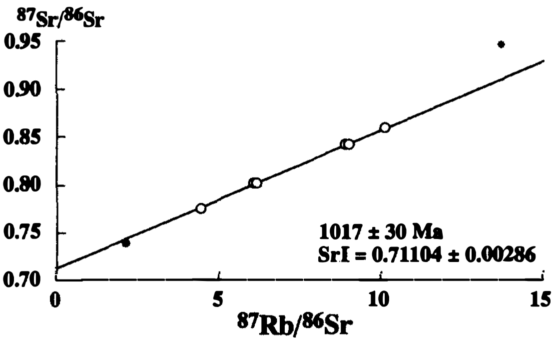

Fig. 8. Rb-Sr whole rock isochron diagram of the Concordia Granite near Garies. Symbols are the same as those in Fig. 6.

Table 3. Rb-Sr and Sm-Nd isotopic data of the Concordia Granite.

Sample No.	Rb(ppm)	Sr(ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr(2\sigma)$	Sm(ppm)	Nd(ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd(2\sigma)$	T_{CHUR}(Ma)	T_{DM}(Ma)
Concordia Granite near Garies										
98082205A	392	129	8.888	0.84049(1)	16.5	98.9	0.1009	0.511951(11)	1094	1618
99082407	265	174	4.440	0.77505(1)	17.8	108	0.09977	0.511900(11)	1161	1670
99082406	350	102	10.10	0.85781(1)	34.5	200	0.1040	0.512012(12)	1030	1579
98082205AY	403	132	8.982	0.84042(1)	15.3	90.4	0.1023	0.511898(12)	1195	1710
98082301Y	313	151	6.075	0.80076(1)	16.2	91.6	0.1067	0.511977(12)	1120	1669
98082301	332	157	6.150	0.80113(1)	13.7	76.3	0.1087	0.511990(10)	1123	1682
Spektakel Suite										
99082705B	216	299	2.100	0.73847(1)	7.23	45.8	0.09545	0.511805(12)	1254	1731
Concordia Granite near Springbok										
98082101	292	63.3	13.69	0.94719(1)	14.6	86.4	0.1019	0.511681(10)	1537	1998

Depleted Mantle (DM) parameters for calculation: $^{143}Nd/^{144}Nd_{(present)}$=0.51315, $^{147}Sm/^{144}Nd_{(present)}$=0.2136.
Chondritic Uniform Reservoir (CHUR) parameters for calculation: $^{143}Nd/^{144}Nd_{(present)}$=0.512638, $^{147}Sm/^{144}Nd_{(present)}$=0.1966.

MgO, CaO and Na_2O have near constant abundances. Trace elements Ba and Zr decrease, and Sr increases, with increasing SiO_2 content. Nb, Rb and Y are highly variable against SiO_2 content. The variations in major and trace element abundances of the Concordia Granite in the OCD are similar to those in the Concordia Granite near Garies.

The Concordia Granite near Garies has a Rb-Sr whole rock isochron age of 1017±30 Ma with an initial Sr isotopic ratio (SrI) of 0.71104±0.00286 (Fig. 8). The samples of the Spektakel Suite and Concordia Granite near Springbok are not plotted on this isochron. The latter is not plotted on the isochron of the Concordia Granite in the OCD of Clifford *et al.* (1995), but plots above the isochron, indicative of gained radiogenic strontium by

Table 4. Whole rock chemical compositions of the Nababeep Granite Gneiss and charnokite.

	Nababeep Granite Gneiss										
	High NdI Group							Low NdI Group			
Sample No.	98082204A	98082204B	99082409A	98082304N	98082001N	98082302A	98082302B	99082401A	98082309	99082411A	99082412
SiO2(wt%)	57.57	65.89	70.61	73.61	74.07	77.30	78.74	64.63	68.21	68.93	69.06
TiO2	2.10	1.15	0.40	0.14	0.22	0.51	0.35	0.81	0.74	0.62	0.59
Al2O3	14.35	14.02	13.60	14.17	13.84	10.25	10.15	14.93	14.33	13.77	14.21
FeO*	8.20	4.85	3.42	1.17	1.70	3.27	1.92	4.66	3.93	3.51	3.28
MnO	0.14	0.14	0.08	0.02	0.05	0.04	0.02	0.09	0.06	0.07	0.06
MgO	2.70	1.82	0.19	0.24	0.40	0.77	0.61	1.51	0.92	0.86	0.80
CaO	5.27	3.06	1.37	1.06	1.03	1.70	1.41	3.55	2.74	2.11	2.29
Na2O	3.39	3.66	3.44	3.23	2.94	1.45	1.50	3.31	3.12	2.90	3.03
K2O	2.28	2.82	5.27	5.93	5.35	3.99	4.11	4.36	4.29	5.36	5.16
P2O5	0.94	0.39	0.06	0.00	0.05	0.02	0.02	0.31	0.18	0.18	0.18
L.O.I.	0.37	0.44	0.30	0.54	0.34	0.67	0.61	0.20	0.44	0.32	0.22
Total	97.31	98.24	98.74	100.11	99.99	99.97	99.44	98.36	98.96	98.63	98.88
Ba(ppm)	1024	328	645	237	360	675	709	1676	1119	959	1008
Co	-	-	-	n.d.	3	10	-	-	12	-	-
Cr	50	30	3	171	107	208	25	14	163	10	11
Cu	-	-	-	7	8	25	-	-	17	-	-
Nb	27	34	32	7	9	5	3	22	19	22	16
Ni	17	12	n.d.	91	59	103	4	n.d.	86	5	3
Rb	248	251	258	383	268	197	194	199	191	285	254
Sr	542	150	57.9	59.0	87.3	147	149	367	226	164	177
V	113	69	4	4	14	53	26	75	58	42	43
Y	56	48	90	58	40	7	8	46	38	59	41
Zn	-	-	-	36	51	57	-	-	74	-	-
Zr	597	363	545	106	129	319	222	250	262	315	311

							Charnokite	
Sample No.	98082308	99082411B	98082105N	98082103B	98081903	98082202	98082005N	98082108N
SiO2(wt%)	70.86	71.25	72.32	73.47	73.85	74.52	65.40	69.91
TiO2	0.46	0.59	0.45	0.24	0.58	0.38	1.12	0.60
Al2O3	13.42	13.11	13.83	13.61	12.07	12.58	14.38	14.16
FeO*	2.96	2.81	2.46	1.64	2.97	2.26	5.37	2.41
MnO	0.07	0.06	0.05	0.03	0.05	0.04	0.08	0.11
MgO	0.82	0.75	0.62	0.24	0.64	0.53	1.45	0.53
CaO	1.96	1.68	1.84	1.00	1.64	1.91	3.43	3.16
Na2O	3.09	2.73	2.74	2.52	2.23	2.48	2.83	3.15
K2O	5.06	5.48	5.41	6.78	4.98	4.40	3.80	4.42
P2O5	0.08	0.16	0.06	0.00	0.09	0.06	0.30	0.11
L.O.I.	0.31	0.37	0.33	0.52	0.38	0.22	0.44	0.75
Total	99.09	98.99	100.11	100.05	99.48	99.38	98.60	99.31
Ba(ppm)	785	920	704	349	695	622	961	1005
Co	10	-	7	3	10	8	16	7
Cr	146	6	97	155	161	128	116	114
Cu	8	-	18	9	11	11	11	9
Nb	20	21	19	n.d.	18	14	17	20
Ni	84	n.d.	59	75	115	65	58	63
Rb	239	297	287	324	328	212	144	162
Sr	161	155	103	58.9	84.6	93.5	272	242
V	41	33	28	6	29	26	74	36
Y	57	46	34	11	54	37	39	23
Zn	53	-	27	29	46	35	108	54
Zr	181	274	184	123	274	200	407	254

L.O.I. : Loss on ignition, n.d. : not detected.

incorporation of metasedimentary material (samples 10 and 64 of Clifford *et al.*, 1995). In the Sm-Nd system, this granite does not indicate a clear isochron, because the variation range of the Sm/Nd ratio is narrow (Table 3). The mean model initial Nd isotopic ratio, using the 1017 Ma Rb-Sr whole rock isochron age of the Concordia

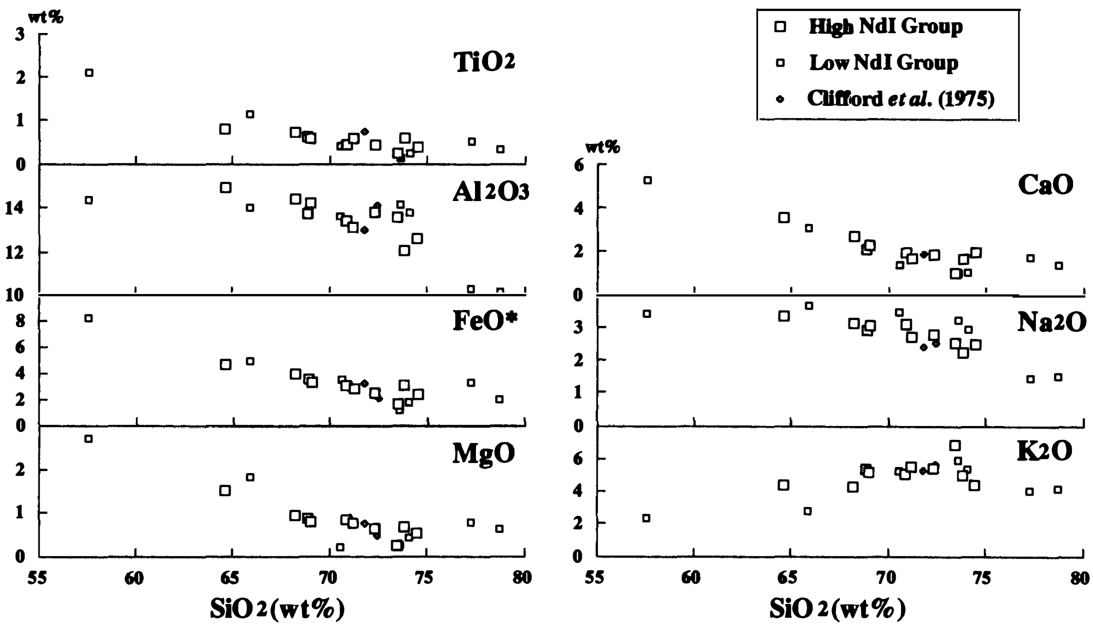

Fig. 9. SiO_2–oxide diagram of the Nababeep Granite Gneiss.

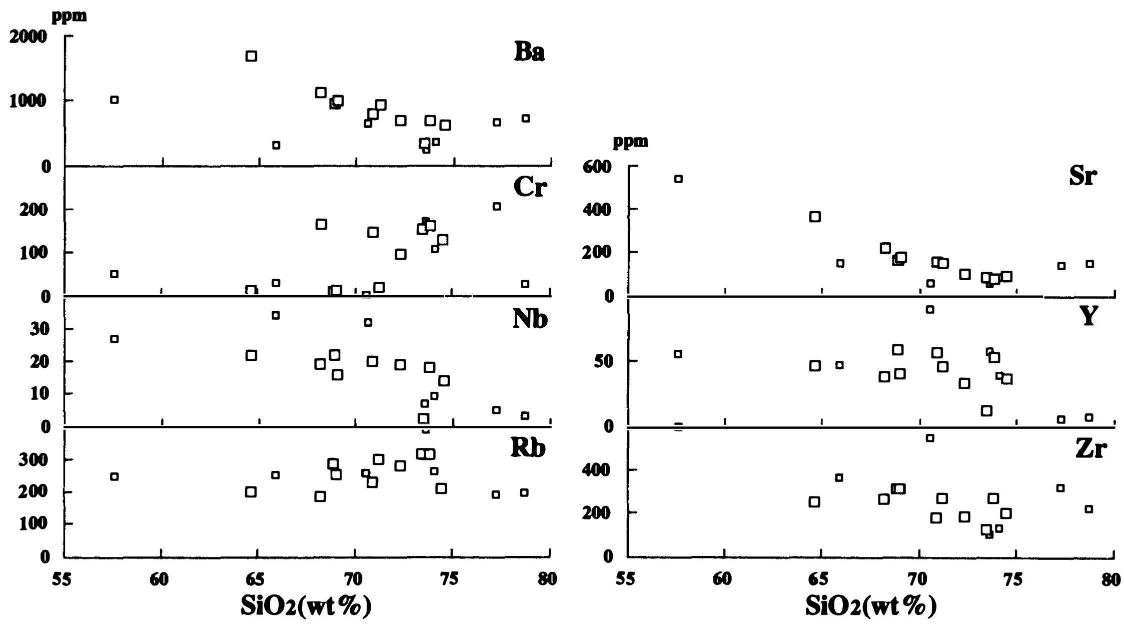

Fig. 10. SiO_2–trace element diagram of the Nababeep Granite Gneiss. Symbols are the same as those in Fig. 9.

Granite near Garies, is 0.511263.

Sm-Nd model ages, using Chondritic Uniform Reservoir (CHUR) and depleted mantle (DM), for the Concordia Granite near Garies are in the narrow ranges from 1030 to 1195 Ma and from 1579 to 1710 Ma, respectively. The model ages of the Concordia Granite near Springbok are 1537 and 1998 Ma, which are older than those near Garies. The model ages of the Spektakel Suite (1254 and 1731 Ma) are similar to those of the Concordia Granite near Garies.

4.2. *Nababeep Granite Gneiss*

The SiO_2 content of the Nababeep Granite Gneiss ranges from 57.6 wt% to 78.7 wt% (Table 4). The variation in major and trace element abundances is illustrated in Harker diagrams (Figs. 9, 10). Major element contents reported by Clifford *et al.* (1975) are plotted in the same diagrams. Abundances of all major elements except K_2O decrease

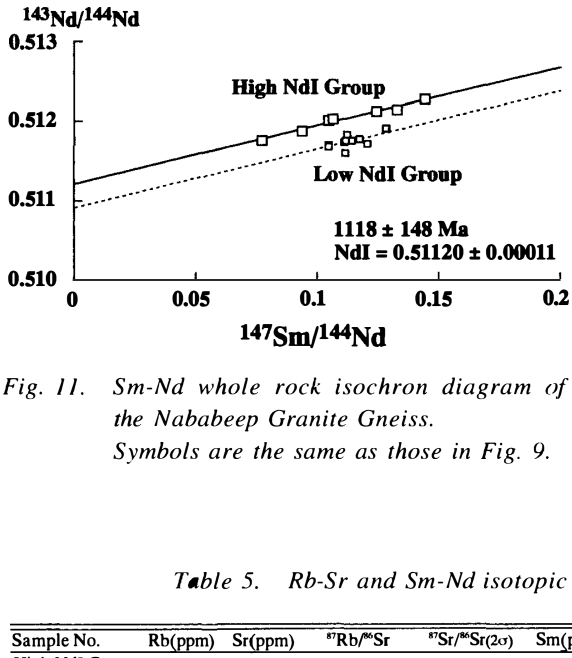

Fig. 11. *Sm-Nd whole rock isochron diagram of the Nababeep Granite Gneiss. Symbols are the same as those in Fig. 9.*

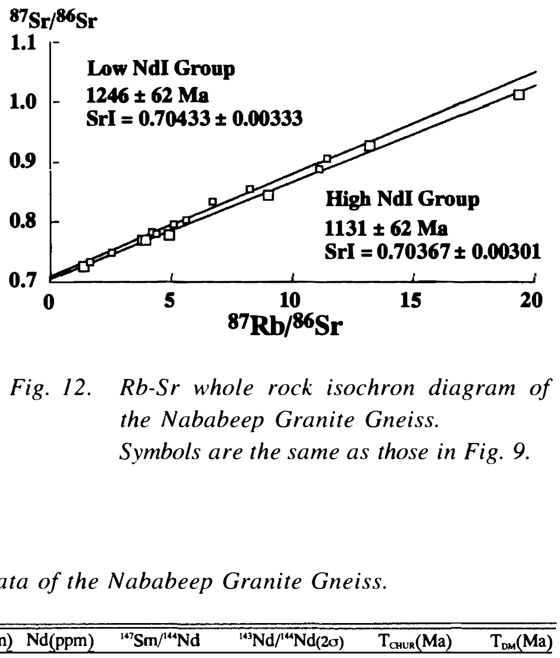

Fig. 12. *Rb-Sr whole rock isochron diagram of the Nababeep Granite Gneiss. Symbols are the same as those in Fig. 9.*

Table 5. *Rb-Sr and Sm-Nd isotopic data of the Nababeep Granite Gneiss.*

Sample No.	Rb(ppm)	Sr(ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr(2\sigma)$	Sm(ppm)	Nd(ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd(2\sigma)$	T_{CHUR}(Ma)	T_{DM}(Ma)
High NdI Group										
98082001N*	268	87.3	8.998	0.84237(1)	7.63	37.2	0.1240	0.512121(11)	1085	1746
98082204A*	248	542	1.326	0.72493(1)	22.6	128	0.1065	0.512019(12)	1047	1606
98082204B*	251	150	4.877	0.77775(1)	13.5	78.2	0.1045	0.511995(12)	1064	1610
98082302A*	197	147	3.904	0.76877(1)	1.72	11.1	0.09374	0.511862(11)	1149	1634
98082302B*	194	149	3.799	0.76834(1)	0.925	7.30	0.0766	0.511758(14)	1180	1546
98082304N*	383	59.0	19.33	1.01062(2)	7.19	30.2	0.1440	0.512267(11)	1075	1928
99082409A*	258	57.9	13.16	0.92595(1)	17.4	79.3	0.1326	0.512141(13)	1183	1893
Low NdI Group										
98081903	328	84.6	11.44	0.90374(1)	10.6	56.1	0.1142	0.511755(10)	1630	2131
98082103B	324	85.9	11.11	0.88753(2)	8.50	49.2	0.1044	0.511671(12)	1595	2057
98082105N	287	103	8.198	0.85289(1)	6.54	32.8	0.1207	0.511707(11)	1864	2357
98082202	212	93.5	6.640	0.83326(3)	8.49	46.0	0.1115	0.511591(12)	1870	2317
98082308*	239	161	4.333	0.78020(1)	10.8	50.8	0.1283	0.511906(10)	1630	2214
98082309*	191	226	2.466	0.74886(1)	9.03	49.3	0.1107	0.511735(10)	1599	2088
99082401A	199	367	1.572	0.73196(1)	13.3	71.9	0.1118	0.511832(12)	1446	1967
99082411A	285	164	5.066	0.79493(1)	13.7	79.8	0.1042	0.511685(11)	1569	2034
99082411B	297	155	5.584	0.80166(1)	9.55	49.2	0.1173	0.511775(12)	1693	2199
99082412	254	177	4.191	0.78064(1)	8.84	47.9	0.1116	0.511757(13)	1577	2074

*collected from upper granulite - faceis area

Depleted Mantle (DM) parameters for calculation: $^{143}Nd/^{144}Nd_{(present)}$=0.51315, $^{147}Sm/^{144}Nd_{(present)}$=0.2136.

Chondritic Uniform Reservoir (CHUR) parameters for calculation: $^{143}Nd/^{144}Nd_{(present)}$=0.512638, $^{147}Sm/^{144}Nd_{(present)}$=0.1966.

with increasing SiO_2 content. Trace element Cr content increases with increasing SiO_2 content. Ba, Nb, Sr, Y and Zr are negatively correlated with SiO_2. Rb content is nearly constant.

The Nababeep Granite Gneiss can be divided into two groups in the Sm-Nd system (Fig. 11). One group has high Nd isotopic ratios and indicates isochron age of 1118±148 Ma with an initial Nd isotopic ratio (NdI) of 0.51120±0.00011. Another group has low Nd isotopic ratios, which give model initial Nd isotopic ratios of *ca.* 0.51091. The former group has a Rb-Sr whole rock isochron age of 1131±62 Ma with an SrI of 0.70367±0.00301 (Fig. 12). The latter group indicates isochron ages of 1246±62 Ma with an SrI of 0.70433±0.00333.

The Nd model ages calculated using CHUR and DM for the Nababeep Granite Gneiss are listed in Table 5. The model ages of the high NdI group range from 1047 to 1183 Ma (T_{CHUR}) and from 1546 to 1928 Ma (T_{DM}). On the other hand, the ages of the low NdI group range from 1446 to 1864 Ma (T_{CHUR}) and from 1967 to 2357 Ma (T_{DM}).

4.3. Metamorphic rocks

The Rb-Sr and Sm-Nd data of the metasedimentary rocks collected from one outcrop do not define isochron ages. This is because of high variability in the Rb-Sr system and narrow variation range in the Sm-Nd system (Table 6).

The Sm-Nd model ages of these metasedimentary rocks are in the narrow range from 1314 to 1429 Ma (T_{CHUR}) and from 1881 to 1996 Ma (T_{DM}). The model ages of the charnokite are 995 Ma (T_{CHUR}) and 1591 Ma (T_{DM}), 1251 Ma (T_{CHUR}) and 1764 Ma (T_{DM}) (Table 6).

Table 6. Rb-Sr and Sm-Nd isotopic data of the metamorphic rocks.

Sample No.	Rb(ppm)	Sr(ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr(2\sigma)$	Sm(ppm)	Nd(ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd(2\sigma)$	T_{CHUR}(Ma)	T_{DM}(Ga)
Metasedimentary rocks										
99082806B	99.8	275	1.050	0.72416(1)	7.11	35.5	0.1210	0.511959(13)	1367	1954
99082806C	226	310	2.117	0.73665(1)	3.31	16.9	0.1181	0.511932(12)	1369	1938
99082806E	80.9	143	1.644	0.73437(2)	8.36	42.7	0.1183	0.511905(13)	1425	1985
99082806F	111	65.3	4.962	0.75491(1)	10.9	55.0	0.1196	0.511915(11)	1429	1996
99082806G	75.9	203	1.085	0.72663(1)	9.04	46.9	0.1167	0.511948(11)	1315	1885
99082806H	76.1	239	0.9210	0.72415(1)	11.2	56.2	0.1201	0.511978(11)	1314	1905
99082806K	68.4	187	1.059	0.72663(1)	8.85	47.9	0.1117	0.511889(12)	1343	1881
99082806M	77.9	210	1.077	0.72589(1)	9.92	50.3	0.1193	0.511952(9)	1351	1930
Charnokite										
98082005N	144	272	1.539	0.72925(1)	11.9	64.7	0.1117	0.512084(11)	995	1591
98082108N	162	242	1.951	0.73759(1)	5.62	32.8	0.1037	0.511875(12)	1251	1764

Depleted Mantle (DM) parameters for calculation: $^{143}Nd/^{144}Nd(present)=0.51315$, $^{147}Sm/^{144}Nd(present)=0.2136$.

Chondritic Uniform Reservoir (CHUR) parameters for calculation: $^{143}Nd/^{144}Nd(present)=0.512638$, $^{147}Sm/^{144}Nd(present)=0.1966$.

5. Discussion

The Rb-Sr whole rock isochron age of 1017 Ma of the Concordia Granite near Garies is interpreted as being its age of emplacement. This is younger than that of the Concordia Granite in the OCD (1105 Ma; Clifford *et al.*, 1995), but coincides with the zircon SHRIMP age for the intrusion (1064 Ma; Robb *et al.*, 1999). This suggests that igneous activity of the Concordia Granite in both near the Garies area and OCD took place at the same time. Thus, the period of activity of the Spektakel Suite, including the Concordia Granite and Rietberg Granite, is the same as in the whole area of the Bushmanland Terrane. The initial Sr isotopic ratio (0.71104) of the Concordia Granite near Garies coincides within an error with 0.709±0.003 (Clifford *et al.*, 1995) in the OCD. On the other hand, Nd model ages of the Concordia Granite near Garies are younger than those in the OCD. The mean εNd value, calculated using the Rb-Sr whole rock isochron age, is –1.24, which is much higher than –7.39 of the Concordia Granite in the OCD (Clifford *et al.*, 1995). Thus, the Sr isotopic composition of source rocks of the Concordia Granite near Garies is similar to that in the OCD, but Nd isotopic compositions of the former differ from those of the latter.

The Nababeep Granite Gneiss can be divided into two groups, one of high Nd isotopic ratio, and another with low Nd isotopic ratio (Fig. 11). We named the former 'the High NdI Group' and the latter 'the Low NdI Group', respectively. In the Harker diagrams (Figs. 9, 10), variations in many elements overlap each other, but variations of Ba, Nb and Sr differ between the two groups. The Rb-Sr whole rock isochron ages (1131±62 Ma and 1246±62 Ma) of both groups of the Nababeep Granite Gneiss, interpreted to be the age of granulite-facies metamorphism, are similar to reported ages from the OCD (Barton, 1983; Clifford *et al.*, 1995). The Sm-Nd whole rock isochron age (1118±148 Ma) of the High NdI Group is similar to the Rb-Sr whole rock isochron age. The large age error is caused by the narrow variation range of the $^{147}Sm/^{144}Nd$ ratio. The isochron age of the High NdI Group, however, is slightly younger than that of the Low NdI Group. This indicates a difference of timing of metamorphism of the two groups. The initial Sr isotopic ratio of the gneiss is much lower than the 0.7151±0.0034 (Clifford *et al.*, 1995) of the gneiss in the OCD. This may be caused by re-equilibration by lower-

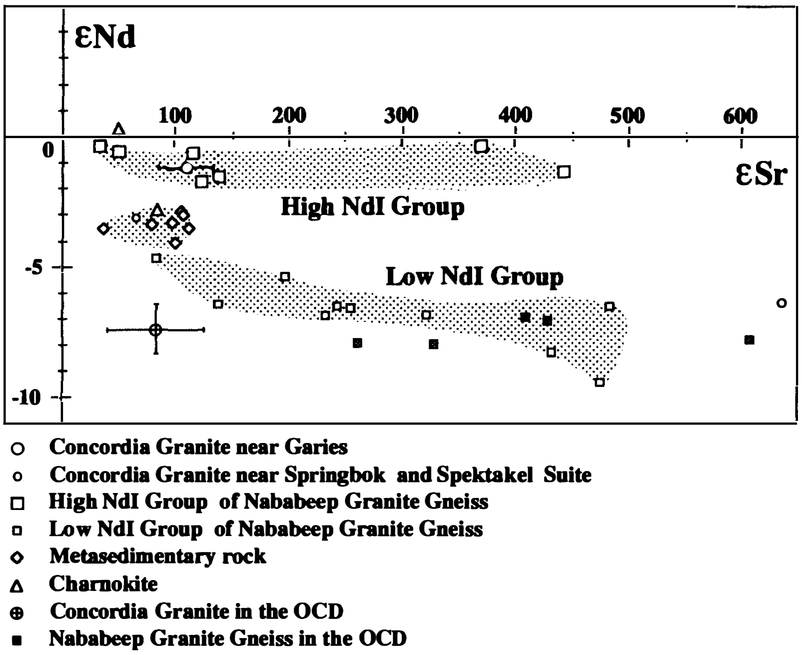

Fig. 13. Initial εSr vs. εNd diagram of the Concordia Granite.
Chondritic Uniform Reservoir (CHUR) parameters for calculation of initial εSr and εNd values are: $^{87}Sr/^{86}Sr(present)=0.7045$, $^{87}Rb/^{86}Sr(present)=0.0827$, $^{143}Nd/^{144}Nd(present)=0.512638$, $^{147}Sm/^{144}Nd(present)=0.1966$. Data of the Concordia Granites near Garies and in OCD are the mean numbers.

upper granulite-facies metamorphism. Large age error (scatter of $^{87}Sr/^{86}Sr$ ratio) may be due to sample collection over a wide area.

The initial εSr and εNd of the Concordia Granite near Garies and model εSr and εNd values of the Nababeep Granite Gneiss and metamorphic rocks calculated using 1017 Ma are plotted on an ε-diagram (Fig. 13). The initial εNd value of the Concordia Granite near Garies differs from that of the Concordia Granite in the OCD (Clifford *et al.*, 1995). The former are within range of the isotopic composition of the High NdI Group of the Nababeep Granite Gneiss, and differ from that of the Low NdI Group that nearly overlap the Nababeep Granite Gneiss in the OCD (Clifford *et al.*, 1995) and metasedimentary rocks. Based on petrogical and geochemical evidence, Raith (1995) suggested that the Concordia Granite is a fractionated S-type granite of lower crust origin, and that the large-scale melting of middle to lower crust must be seen in context with 1.2 Ga high-T, low-P granulite-facies metamorphism. Thus, the Concordia Granite near Garies is likely to have formed from middle to lower crust, having the same isotopic

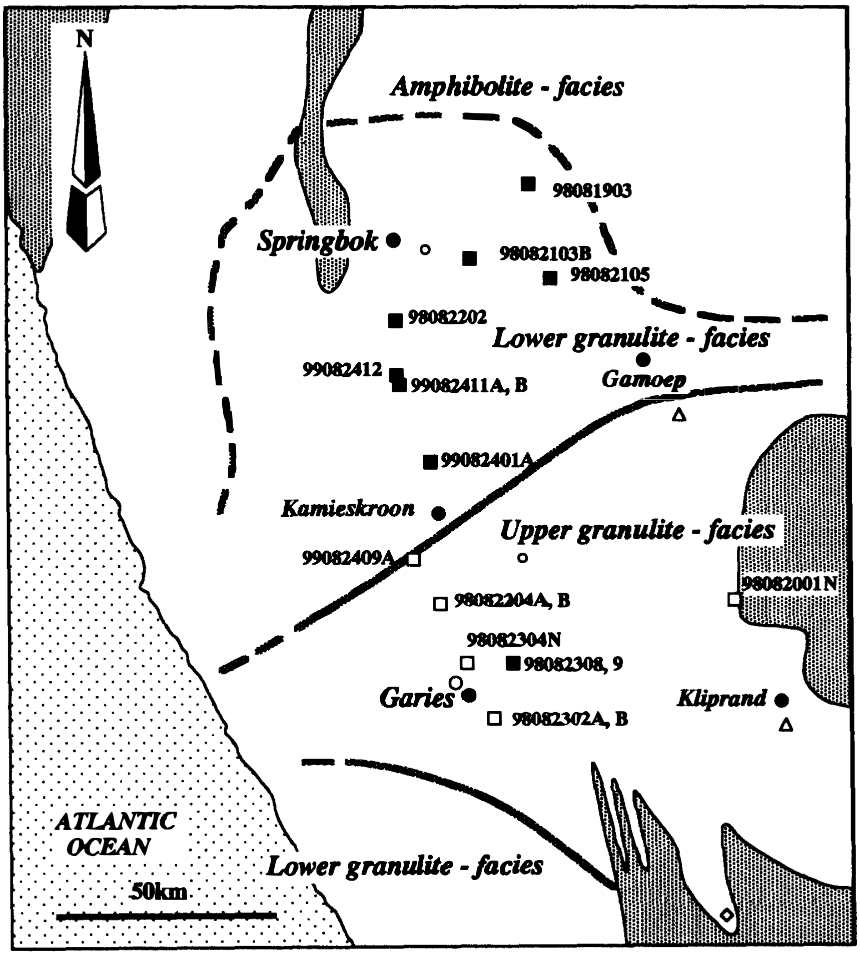

Fig. 14. The distribution of the High and Low NdI Groups of the Nababeep Granite Gneiss and its relationship to the metamorphic zonation indicated by Robb et al. (1999).
Symbols are the same as those in Fig. 13, excluding those of the Nababeep Granite Gneiss. Open squares: High NdI Group; solid squares: Low NdI Group.numbers.

compositions as the High NdI Group of Nababeep Granite Gneiss.

Most of the Low NdI Group are distributed in the northern part of the study area, north of a line between Kamieskroon and Gamoep (Fig. 14). The High NdI Group is distributed to the south of this line. The division between these two areas accords with the boundary between the lower granulite-facies and upper granulite-facies in metamorphic zonation, as defined by Robb *et al.* (1999). The geochemical characteristics of the Little Namaqualand Suite indicate that the magmas were derived from crustal materials (Gibson *et al.*, 1996). This suggests that Nd isotopic compositions of the lower crust, which were source materials of the Nababeep Granite Gneiss, were not uniform, and are different on either side of the line connecting Kamieskroon and Gamoep.

Clifford *et al.* (1995) indicated that Sm-Nd model ages of the Koperberg Suite, the Concordia and Rietberg Granites, the Nababeep Granite Gneiss and the two-pyroxene granulites in the OCD are statistically indistinguishable, and concluded that the continental crust was extracted from the mantle at ~1700–2000 Ma. This is consistent with previous isotope studies in Namaqualand (Reid, 1979a, b; Barton, 1983; Reid *et al.*, 1987), which have documented a major crust- forming event in Eburnian time within the interval of 2000–1700 Ma (Clifford *et al.*, 1995). The Sm-Nd model ages of the Low NdI Group of Nababeep Granite Gneiss (average being 1647 Ma by T_{CHUR} and 2144 Ma by T_{DM}) overlap those ages (Fig. 15). However, the model ages of the Concordia Granite near Garies (average, 1121 Ma by T_{CHUR} and 1655 Ma by T_{DM}), High NdI Group of Nababeep Granite Gneiss (averages are 1112 Ma by T_{CHUR} and 1709 Ma by T_{DM}), the metasedimentary rocks (averages are 1364 Ma by T_{CHUR} and 2059 Ma by T_{DM}) and the charnokites (averages are 1123 Ma by T_{CHUR} and 1678 Ma by T_{DM}), which are distributed south of the line connecting Kamieskroon and Gamoep, are younger than those ages (Fig.

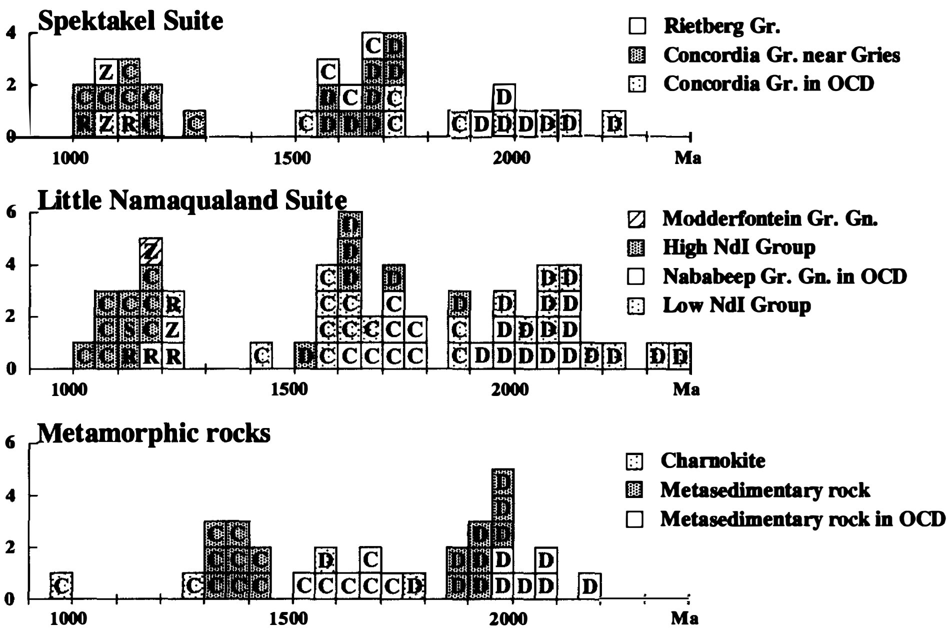

Fig.15. Radiometric age histogram of the Spektakel, Little Namaqualand Suites and metamorphic rocks in the Namaqualand metamorphic complex.
R: Rb-Sr whole rock isochron age, S: Sm-Nd whole rock isochron age, Z: zircon SHRIMP age, C: T_{CHUR} *age, D:* T_{DM} *age.*

15). The age data indicate that the age of the crust-forming event in the southern area is younger than that in the northern area, including the OCD, at ~1100–1700 Ma. Because the rocks of the Low NdI Group are distributed in the southern part, it is thought that a younger crust-forming event overlapped in this part where the older event took place. The line connecting Kamieskroon and Gamoep may not only be a boundary of metamorphic zonation, but a tectonic boundary between crust sections of different ages. This boundary is along the Buffels River Shear Zone (Joubert, 1971).

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