

**ECONOMIC GEOLOGY
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**Sm-Nd and Rb-Sr ISOTOPE SYSTEMATICS OF
RARE-ELEMENT PEGMATITES FROM THE NEW CONSORT
GOLD MINES, BARBERTON MOUNTAIN LAND,
SOUTH AFRICA**

P.D. HARRIS, C.B. SMITH, R.J. HART and L.J. ROBB

• INFORMATION CIRCULAR No. 265

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BARBERTON MOUNTAIN LAND, SOUTH AFRICA**

by

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ABSTRACT

An evaluation of Rb-Sr and Sm-Nd isotopic data for pegmatites at the New Consort Gold Mines produces an age of around 3040 Ma from these bodies. A major period of deformation contemporaneous with the emplacement of the Consort pegmatites occurs during this time period. As the pegmatites cross-cut gold mineralization at the New Consort Gold Mines, they provide a minimum age constraint for the timing of gold mineralization in this area. Trace amounts of garnet from these rare-element pegmatites exhibit extremely high Sm/Nd ratios and unusually radiogenic neodymium concentrations. The extremely high $^{143}\text{Nd}/^{144}\text{Nd}$ ratios measured in the garnets have not, as far as is known, been recorded previously. These extreme isotope compositions allow determinations of model ages to be made independently of the uncertainties in the evolution of the reference reservoir (ie. CHUR or DM) or crustal pre-history. Consequently, Sm-Nd model age determinations on this type of radiogenic garnet can produce accurate age data and may prove to be an additional tool in the dating of highly fractionated pegmatites.

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INTRODUCTION

The use of isotope geochemistry for the purpose of dating granitic pegmatites is almost as old as the technique of radiometric dating itself (Aldrich et al., 1956). The majority of age determinations of pegmatites have been carried out using Rb-Sr isotope determinations on minerals within the granitic pegmatites, and occasionally on whole rocks. This is because of the suitability of the Rb-Sr technique to the mineralogy of the pegmatites. The large differences in the isotopic ratios of these minerals allows for a good spread in the data and produce small errors once the data are regressed (Allsopp et al., 1968; Clark, 1982). Discrepancies recorded in Rb-Sr ages within single minerals of some granitic pegmatites indicate that there is mobility of ^{87}Sr within these magmatic systems (Allsopp et al., 1968; Clark, 1982; Clark and Černý, 1987). This observation is also supported by the anomalously high initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios recorded during Rb-Sr isotopic determinations. More recently, U-Pb single zircon age determinations have been applied to some granitic pegmatites producing accurate ages for these bodies. Unfortunately, the low abundance of zircon within most granitic pegmatites has limited the use of this technique. During a recent study of granitic pegmatites within the Barberton greenstone belt, South Africa, extremely high Sm/Nd ratios were recorded in garnets from these pegmatites (Harris, 1992). The coarse-grained nature of the pegmatites allows for single grain analyses, while the extremely high ratios provide model ages that are independent of reference reservoir uncertainties or crustal pre-histories. The purpose of this paper is to:

- 1) re-evaluate existing Rb-Sr isotopic data from the Consort pegmatites;
- 2) report on new Rb-Sr whole rock and mineral data for the Consort pegmatites;
- 3) report the high Sm/Nd ratios along with the chemical signatures of the pegmatitic garnets; and
- 4) test the merits of the Sm-Nd garnet technique as an additional dating tool for highly fractionated granitic pegmatites.

GEOLOGICAL SETTING

Several granitic pegmatites occur at the New Consort Gold Mines in the north-central part of the Barberton greenstone belt (BGB), South Africa (Figure 1). The major granitoid bodies surrounding this section of the BGB are the Nelspruit batholith (NB) dated at 3106^{+2}_{-3} Ma (Kamo et al., 1990) to the north, and the Kaap Valley Tonalite (KVT) dated at 3227 ± 1 Ma (Kamo et al., 1990) towards the south-southwest. The local tectonostratigraphy at the NCGM comprises footwall amphibolites (Onverwacht Group), and hanging wall metasediments (Fig Tree Group) where a silicious mylonite unit, termed the Consort Bar, occurs at the boundary between these lithologies (Voges, 1986; Tomkinson and Lombard, 1990; Tomkinson, in prep.). The major gold mineralized zone is located at the contact

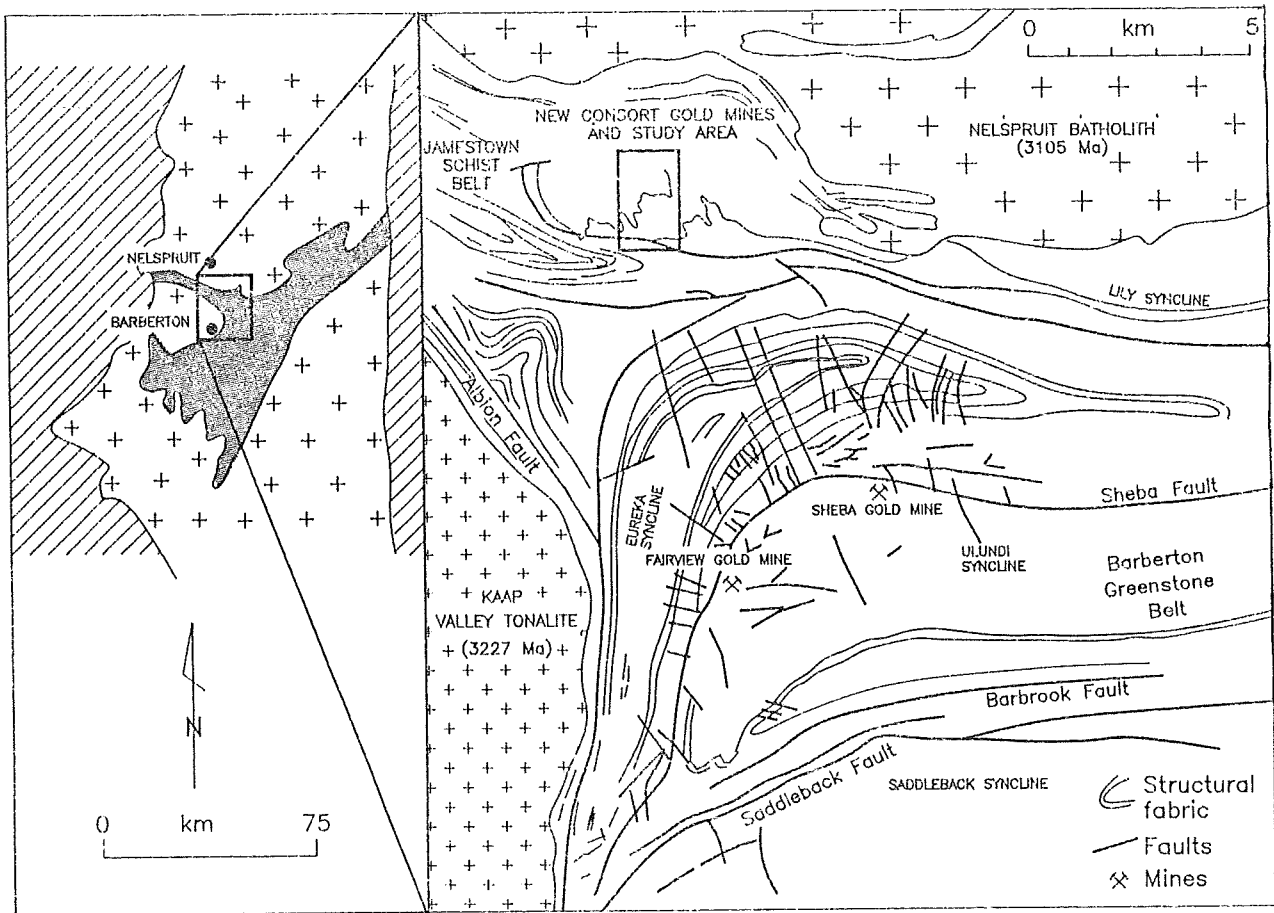


Figure 1: Locality map of the New Consort Gold Mine area in relation to the complexly deformed north-central portion of the Barberton greenstone belt, South Africa (modified after Anhaeusser, 1976, 1986).

between the metasediments and the amphibolites, just below the Consort Bar. The Consort lithologies, and the gold mineralization, are intruded by a suite of rare-element pegmatites, which exploit several different structural sites formed during a protracted deformational event (Harris, 1992; Harris et al., 1993). It is these pegmatites that are the subject of this paper. Three chemically distinct types of pegmatites are found within the mine workings, namely albite, albite-spodumene and K-feldspar-albite pegmatites. The pegmatites may be homogeneous or zoned, and exhibit well-defined differentiation trends, both within the individual bodies and through the suite as a whole. The least fractionated pegmatites are the K-feldspar-albite variety, with the sequence extending through the albite-spodumene pegmatites, to the highly fractionated albite bodies (Harris et al., 1993). The pegmatites consist mainly of quartz, albite, K-feldspar, spodumene (in some pegmatites), and muscovite, with accessory amounts of Ta-oxides, garnet, tourmaline and gahnite (zinc spinel).

ANALYTICAL METHODS

Microprobe analysis

Major element analyses of the garnets were performed at the University of Cape Town on an automated Caneca electron microprobe, using on-line Bence-Albee (1968) correction procedures. A total of twenty one analyses were carried out on garnets from three different pegmatite varieties.

Rare earth element analysis

Garnet REE contents were obtained by instrumental neutron activation analysis (INAA) following a technique modified after Erasmus et al. (1977). The garnets were irradiated in an Oak Ridge-type reactor at Pelindaba (South Africa) for 3 days, and then counted 3 days, 12 days and 30 days respectively after irradiation. Counting times employed were 1 hour for the first count, and then 4 hours for each of the subsequent counts. Because it is important to ensure that the gamma signal counted on the detector comes from the body of the garnets and not from residual surface contamination, special care was taken in the cleaning of the garnets prior to irradiation. The garnets were boiled individually in a diluted mixture of HNO_3 , and HCl for 1 hour before encapsulation in a quartz vial; the garnets were removed from the capsules after irradiation, and the cleaning procedure was repeated. The total neutron flux received by each sample was measured by using a flux monitor in the form of steel wire wrapped around the outside of the vial. Background counts were performed regularly throughout the experiment.

Isotope analysis

All sample fractions weighed approximately 0.1 grams prior to dissolution. Garnet and muscovite samples were hand picked to select the most suitable separate for isotope analysis. The garnet separates were leached in distilled 6N HCl for 4 to 6 hours before dissolution. Muscovite samples were cleaned by ultrasonic agitation and then washed in distilled water. Clean teflon beakers were used for dissolution of the whole rock and mineral separates. Approximately 2 to 6 ml of distilled 48% HF acid with 1 to 2 millimetres of HNO_3 acid were combined with the sample for the dissolution process. The HNO_3 served as an oxidizing agent to raise the boiling point of the mixture. The sample beakers were then heated until near boiling, after which the beakers were covered and left on a hot plate for 2 to 3 days. After this time period the remaining acid in the beaker was dried down and 6N HCl was added to ensure that complete dissolution of the sample had occurred. Rb-Sr samples were spiked prior to dissolution whereas Sm-Nd samples were split into a natural and a spiked sample after dissolution. Sm-Nd sample dissolutions were split 2:1, with the smaller split being spiked for both Sm and Nd. Concentrations of Sm and Nd were determined from the spiked sample, while the Nd isotopic ratios were determined from the natural split. Ion-exchange chromatography was utilized to extract the elements necessary for isotopic analysis. Rb and Sr were separated using the method of Aldrich (1956) while the Sm and Nd were separated using a variation of this method described by Richard et al. (1976). Rb, Sr, Sm and Nd concentrations were measured on a MM30 mass spectrometer, while $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were measured using a VG354 mass spectrometer.

Blank levels were below 2ng for Rb and Sr, while blank levels during the Sm and Nd separation were below 10pg. Consequently, blank corrections using 10pg for both Sm and Nd were applied to the analyses. The blank-corrected Sm-Nd ages do not differ significantly from the uncorrected ages, and these ages do not change by more than 2 Ma. Errors for the $^{147}\text{Sm}/^{144}\text{Nd}$ ratios were calculated from individual Sm and Nd concentration errors multiplied by magnification factors as $\sqrt{A^2+B^2}$ where A and B are the percentage error components on ratio measurements for Sm and Nd.

The processing and regression of the Rb-Sr and Sm-Nd isotopic data were carried out using the program "GEODATE" version 2.2 of Eglington and Harmer (1991).

Rb-Sr AND Sm-Nd ISOTOPE DATA FOR THE CONSORT PEGMATITES

Previous isotopic studies on the Consort pegmatites have been undertaken by Allsopp et al (1968), Harris (1992) and this study. Apart from the Sm-Nd garnet age determinations all other age estimates have been obtained using Rb-Sr systematics. Allsopp et al. (1968) carried out Rb-Sr isotopic analyses on whole rock pegmatite samples as well as muscovite, feldspar and spodumene separates. The results of this data have been corrected to the new decay constant (λ) of $1.42 \times 10^{-11} \text{y}^{-1}$ for ^{87}Rb and model ages for all the data are calculated using an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (R_0) of 0.700.

Rb-Sr whole rock and mineral data

Table 1 lists the Rb and Sr concentrations and ratios of all whole rock samples from the Consort pegmatites. A mean of the whole-rock model ages for 10 samples from Allsopp et al. (1968) produces an age of 2999 ± 74 Ma, while the average model age for 4 samples from Harris (1992) is 3114 ± 121 Ma. A total mean of all the available whole-rock model age data provides an age of 3058 ± 60 Ma. A recalculation of the whole-rock regression data of Allsopp et al. (1968) using the new decay constant produces a date of 2973 ± 86 Ma (MSWD=4.673) with an initial ratio of 0.7491 ± 0.1106 (Figure 2). All the data of Harris (1992) regresses to an age of 3080 ± 54 Ma (MSWD=5.238) with an initial ratio of 0.7283 ± 0.0258 (Figure 3). Regression of all the whole-rock data available from the Consort pegmatites produces an age of 3023 ± 49 Ma (MSWD=5.429) with an initial ratio 0.7411 ± 0.0305 (Figure 4).

Seven muscovite, 2 plagioclase and 1 spodumene mineral separates were analyzed and presented by Allsopp et al. (1968), while Harris (1992) presented Rb-Sr data for 2 duplicate muscovite separates from the Consort pegmatites. An additional duplicate Rb-Sr isotope analysis of spodumene is presented along with the previously published analyses in Table 2. The muscovite separates of Allsopp et al. (1968) produce a mean model age of 2888 ± 58 Ma, while the data from Harris (1992) produces variable duplicate ages with a mean age of 3077 ± 60 Ma. Model ages for the spodumene separates provide ages of ≈ 2609 Ma (Allsopp et al., 1968) and ≈ 2785 Ma. The model ages for the plagioclase data are unrealistic and indicate disturbance of the Rb-Sr systematics within this mineral. The average Rb-Sr whole-rock model age and the errorchron age of 3058 ± 60 Ma and 3023 ± 49 Ma, respectively, provide a date of around 3040 Ma for Rb-Sr systematics from the Consort pegmatites.

TABLE 1. Whole rock Rb-Sr isotopic data for the Consort pegmatites

SAMPLE	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	Tm (Ma) $R_0=0.7$
B251 ^a			94.75	4.784	2972
B253 ^a			19.79	1.659	3333
OG103 ^a			97.59	5.28	3230
OG104 ^a			156.7	7.306	2908
OG105 ^a			168.5	8.075	3017
OG107 ^a			40.02	2.412	2950
OG108 ^a			34.88	2.193	2952
OG110 ^a			22.60	1.719	3106
OG111 ^a			38.87	2.392	3001
AA6 ^a			77.49	4.064	2993
SH ^b	846.1	12.48	1462	66.709 ± 12	3107
MR ^b	243.0	10.65	93.62	4.9795 ± 13	3148
NS ^b	273.4	10.96	104.4	5.2700 ± 8	3017
PV ^b	224.5	40.55	17.26	1.5009 ± 3	3195
Average Rb-Sr whole rock model age					3058 ± 60

^a Data from Allsopp et al.(1968)

^b Data from Harris (1992)

Sm-Nd isotope data

Isotopic data from the garnets in the Consort pegmatites are presented in Table 3. It is clear that the Consort pegmatite garnets are characterized by extremely high Sm/Nd and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios compared to typical terrestrial Nd isotopic compositions. Such high ratios have not been previously recorded. A Nd evolution diagram for the Consort pegmatite garnets is shown in Figure 5 and demonstrates how the extremely high $^{143}\text{Nd}/^{144}\text{Nd}$ ratios allow for the calculation of a model age that is essentially independent of the reference reservoir or any pre-crustal history. Irrespective of whether T_{DM} or T_{CHUR} is used, the model ages are indistinguishable. The model ages do, however, depend on how accurately the Sm/Nd ratios can be measured. Errors in the measurements of the Sm and Nd concentrations result in large errors on the model age determination, and this is demonstrated in Table 3 by sample PDHGNT when compared to the more accurately measured concentrations. The Sm-

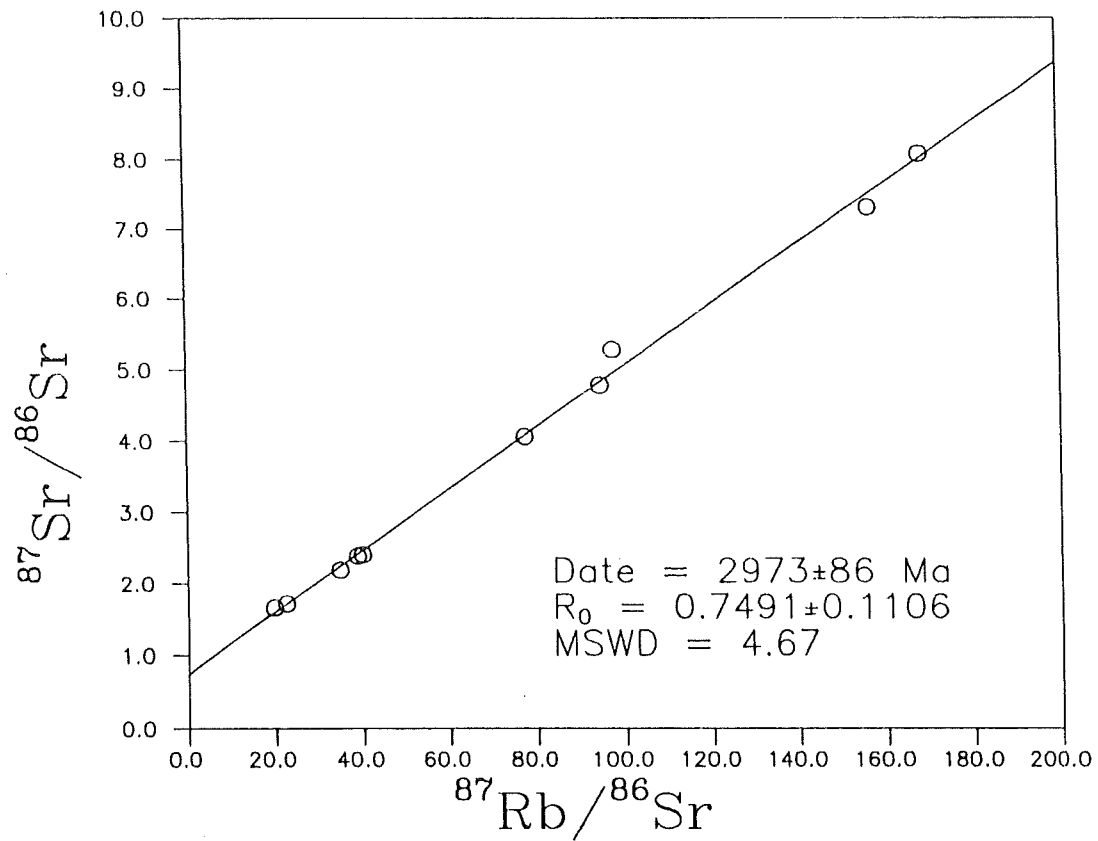


Figure 2: Rb-Sr isochron diagram of whole rock pegmatite samples from the data of Allsopp *et al.* (1968). The data have been regressed using the new decay constant for ^{87}Rb .

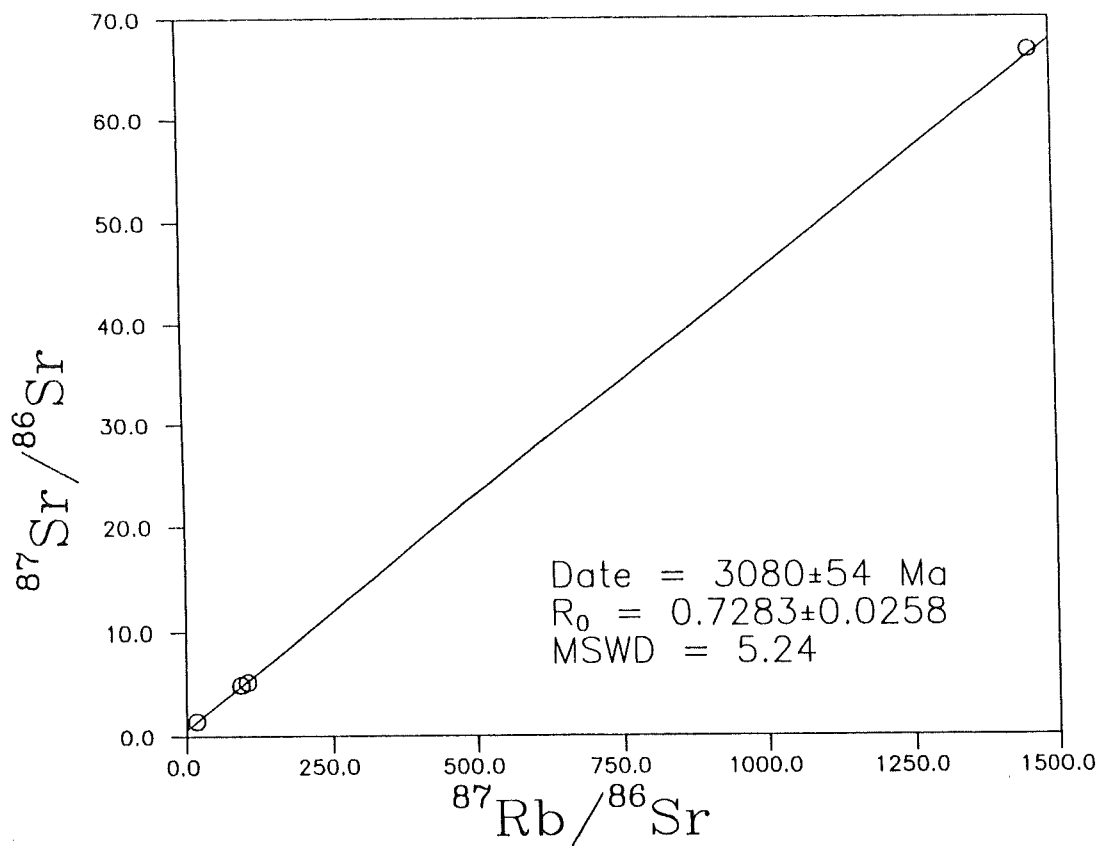


Figure 3: Rb-Sr isochron diagram of whole rock pegmatite samples from Harris (1992).

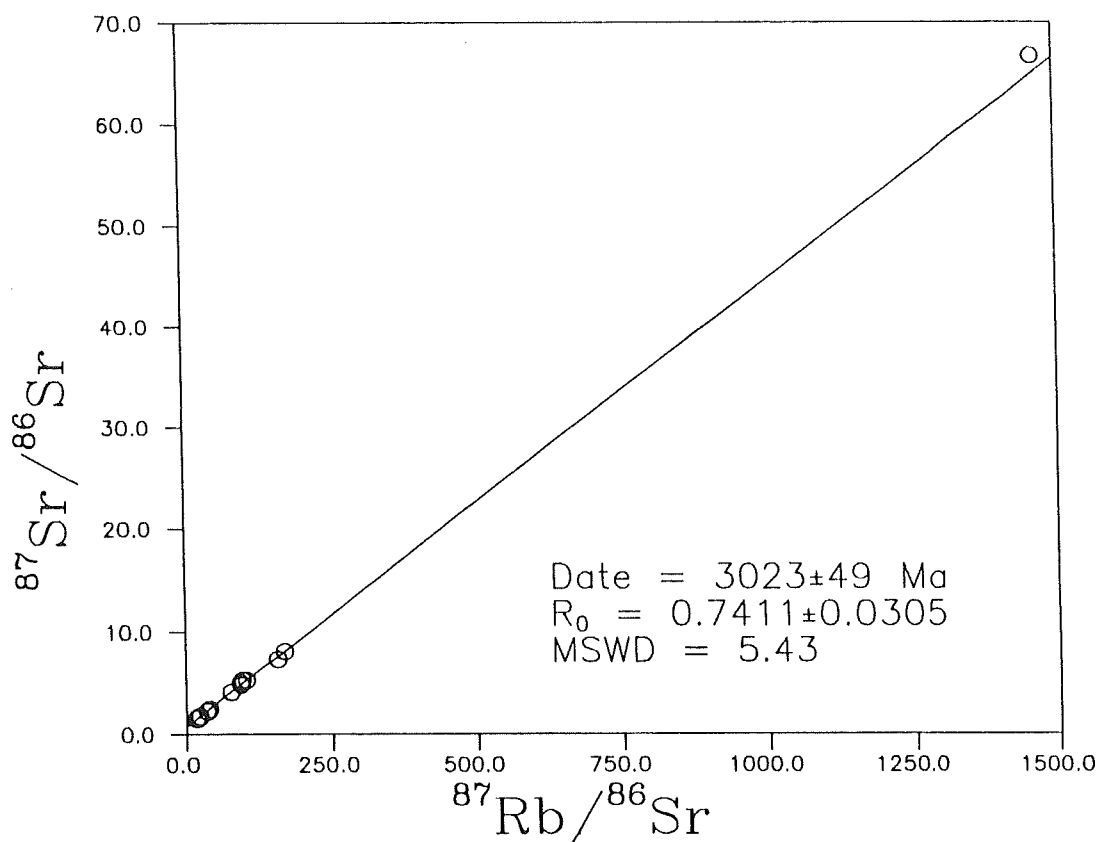


Figure 4: Rb-Sr isochron diagram of all the whole rock pegmatite samples available (data from Allsopp et al., 1968 and Harris, 1992).

Nd model ages from three garnets are within analytical error and provide a mean age of 3036 ± 19 Ma (Table 3). These model ages are also within analytical error of the ages interpreted from the Rb-Sr data (≈ 3040 Ma). The significance of this date will be discussed in a later section.

GARNET GEOCHEMISTRY

The Sm-Nd isotopic data from the pegmatitic garnets are unusual with respect to normal terrestrial Sm-Nd concentrations and isotopic ratios. It is therefore necessary to examine the chemistry of these garnets and to try and establish reasons for these high isotopic ratios. The following section describes the chemical features of the pegmatitic garnets, while possible explanations for these unusual trends will be discussed in a later section.

Major element chemistry

Major element concentrations of garnets from three individual pegmatite bodies have been averaged and these are presented in Table 4. Available published data from other pegmatite

TABLE 2. Rb-Sr isotopic data for mineral separates from the Consort pegmatites

SAMPLE	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	Tm (Ma) $R_0=0.7$
Muscovite					
SHM(a) ^b	7683	99.50	41876	1906.9 ± 1.3	3135
SHM(b) ^b	7875	98.11	42529	1862.8 ± 1.5	3018
B251M ^a	2864	52.45	466.1	20.624	2950
B252M ^a	1951	25.16	2416	100.49	2852
B253M(a) ^a	2090	35.31	556.7	23.691	2852
B253M(b) ^a	2096	34.23	631.6	26.900	2865
OG103M ^a	2159	29.35	1383	56.858	2805
AA6M(a) ^a	7560	93.93	8078	344.75	2940
AA6M(b) ^a	7504	94.36	7611	328.30	2971
Spodumene					
SHSP(a)	128.2	1.88	903.3	37.27 ± 6	2775
SHSP(b)	92.63	1.28	1118.5	45.094 ± 20	2795
AA6S ^a			140.97	6.021	2609
Plagioclase					
B253P ^a			3.464	1.056	6889
AA6P ^a			4.069	1.637	14594

^a Data from Allsopp et al.(1968)^b Data from Harris (1992)

TABLE 3. Sm-Nd isotopic data from garnet separates of the Consort pegmatites

SAMPLE	Nd (ppm)	Sm (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	T _{DM} (Ma)	T _{CHUR} (Ma)
PDHGNT	1.291 ± 50	15.069 ± 1	7.299	0.658042 ± 42	3099 ± 126	3096 ± 126
50/1	1.323 ± 8	15.406 ± 1	7.276	0.654676 ± 28	3038 ± 19	3035 ± 19
50/2	1.272 ± 8	15.418 ± 3	7.584	0.660821 ± 30	3037 ± 19	3034 ± 19

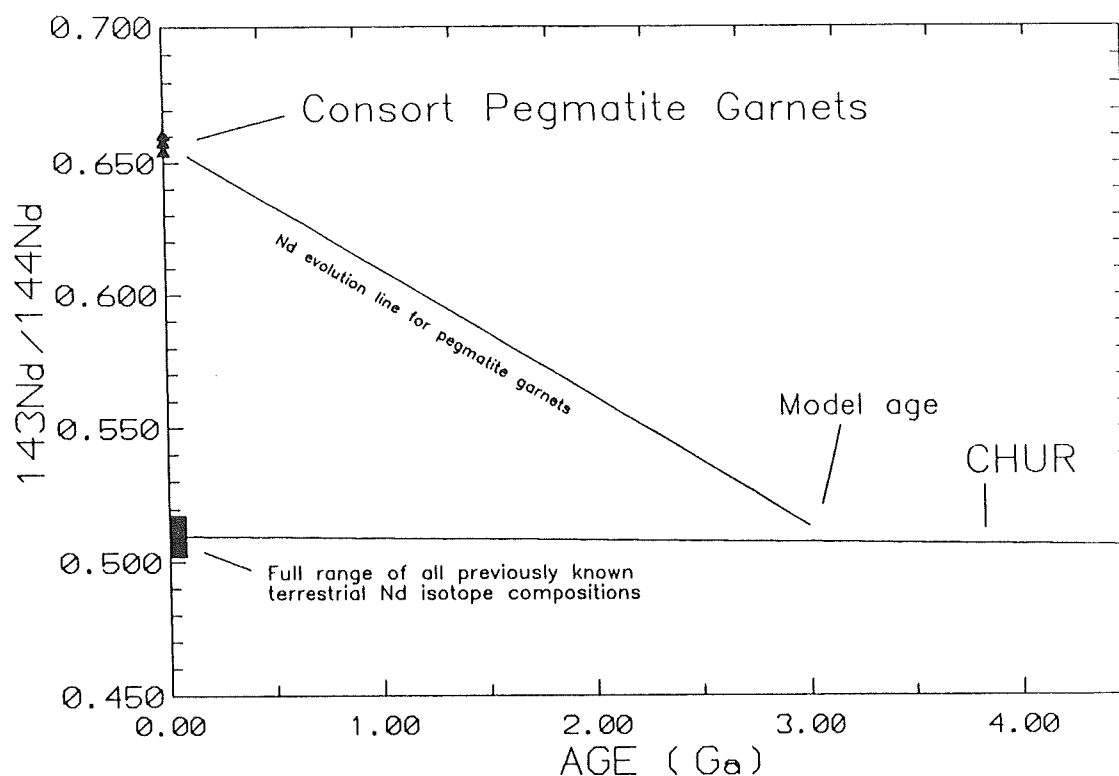


Figure 5: Neodymium evolution diagram for the Consort garnets.

TABLE 4. Average major element concentrations for garnets from individual pegmatites at the New Consort Gold Mines

	MR Pegmatites (n=10)	PC Pegmatite (n=6)	Shires Pegmatites (n=5)
Wt%			
SiO ₂	36.00	36.44	36.10
TiO ₂	BDL	BDL	BDL
Al ₂ O ₃	21.08	21.39	21.26
Cr ₂ O ₃	BDL	BDL	BDL
FeO	30.09	17.27	27.44
MnO	12.55	25.33	15.33
MgO	0.68	0.13	0.43
CaO	0.22	0.30	0.20
Na ₂ O	BDL	BDL	BDL
TOTAL	100.62	100.86	100.76
Atomic proportions based on 12 oxygens			
Si	2.955	2.977	2.957
Ti	-	-	-
Al	2.038	2.060	2.053
Cr	-	-	-
Fe	2.066	1.177	1.880
Mn	0.873	1.786	1.064
Mg	0.083	0.016	0.052
Ca	0.019	0.026	0.018
Na	-	-	-

BDL:- Below detection limit

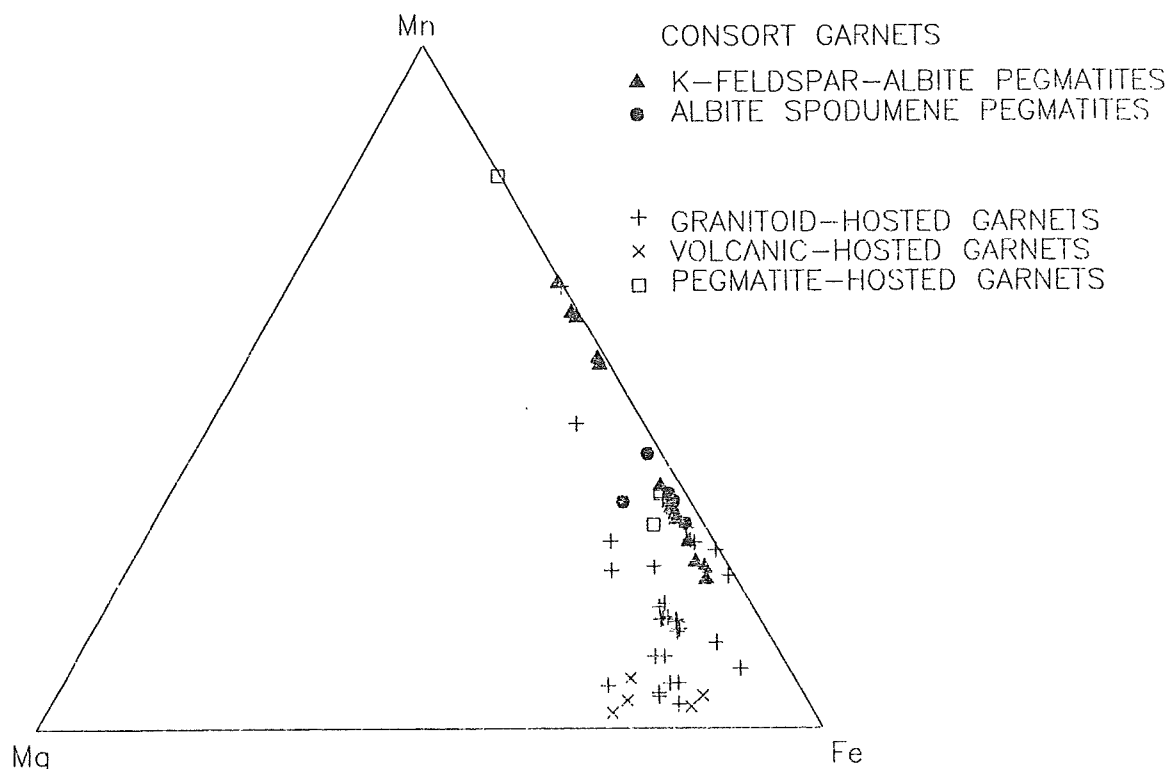


Figure 6: Ternary plot of Mn-Fe-Mg for igneous garnets compared to pegmatite garnets from the New Consort Gold Mines, Barberton greenstone belt. Garnet analyses are plotted as ionic proportions based on 12 oxygens. Granitoid garnet compositions are from Du Bray (1988). Dacitic to andesitic garnet data are from Irving and Frey (1978), while the pegmatite garnet data are from Allan and Clarke (1981).

garnets, along with granitic and acid volcanic garnet data, are plotted with our data for comparison. Garnets from the individual Consort pegmatites exhibit a fairly wide variation in their Fe and Mn concentrations (Figure 6). Work on garnet zonation within pegmatites (Baldwin and Von Knorring, 1983; MacLeod, 1992) indicates that there are wide variations in Mn and Fe contents within garnets from different pegmatite zones and individual garnets. The large variations observed in the garnets from the Consort pegmatites are thought to be due to similar variations within the zonation of the minerals. Ternary plots of Mn-Fe-Mg and Mn-Fe-Ca(x10) (Figures 6 and 7) indicate that the garnets are spessartine-rich with high Mn and Fe concentrations, and low Ca and Mg contents. There is a significant difference in the major element concentrations of the Consort pegmatite garnets compared to granitic and acid volcanic garnets. However, when the garnets are compared to other pegmatite garnets they show typical major element concentrations (Figures 6 and 7).

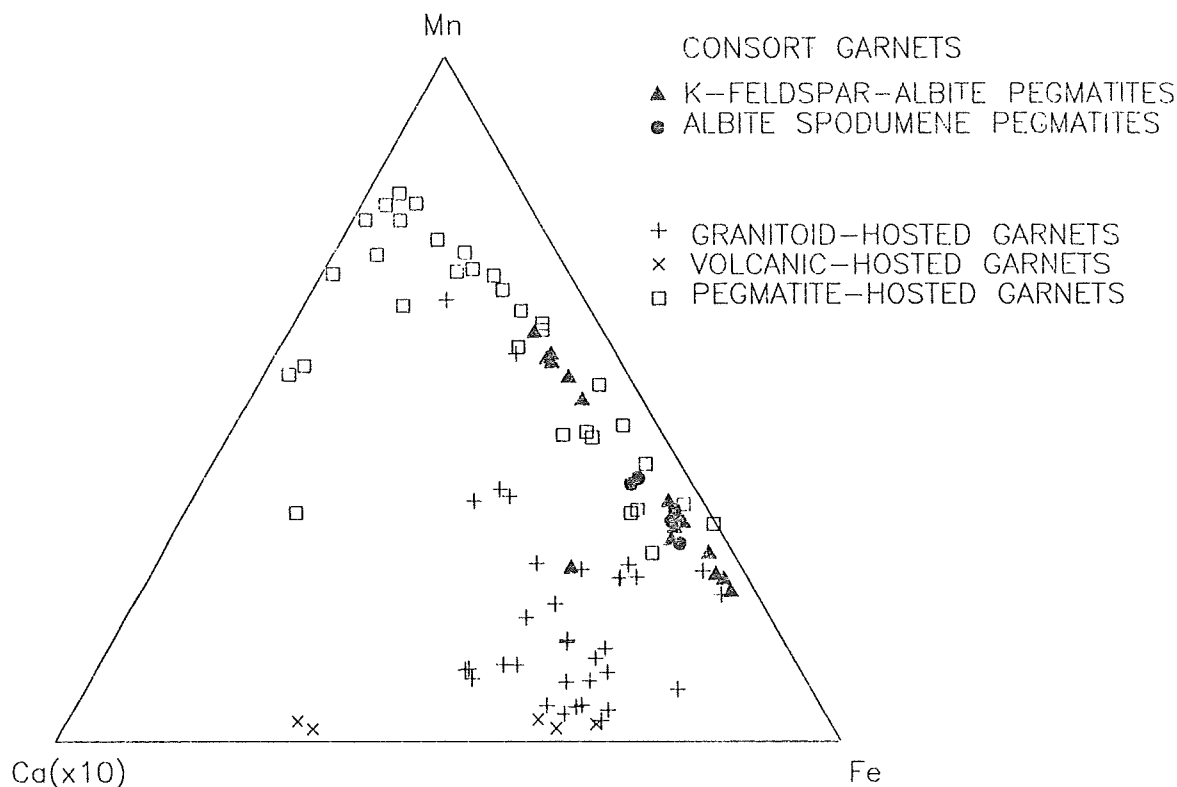


Figure 7: Ternary plot of Mn-Fe-Ca(x10) for igneous garnets compared to pegmatite garnets from the New Consort Gold Mines, Barberton greenstone belt. Garnet analyses are plotted as ionic proportions based on 12 oxygens. Granitoid garnet data are from Du Bray (1988), Vernum and Meyer (1979), Allan and Clarke (1981) and Phillips et al. (1981). Dacitic and andesitic garnet data are from Irving and Frey (1978). Data from pegmatite garnets are from Baldwin and Von Knorring (1983), Hornung and Von Knorring (1962), Neiva (1975) and Hall (1965).

REE chemistry

The average REE pattern for the Consort pegmatite garnets is plotted on a chondrite-normalized diagram and compared to published data from igneous garnets (Figure 8 and Table 5). Sm and Nd concentrations were obtained by isotope dilution, while REE concentrations below detection are plotted at the instrumental detection limits for INAA. At present there is very little published REE data on felsic igneous garnets, and little or no data for pegmatitic garnets. Consequently the REE patterns of the Consort pegmatite garnets are compared to granitic and felsic volcanic garnets (Du Bray, 1988; Irving and Frey, 1978; Schnetzler and Philpotts, 1970).

The REE patterns for the Consort pegmatite garnets are HREE enriched and have a pronounced negative Eu anomaly, which is typical of felsic igneous garnets. The Consort pegmatite garnets, however, have extremely low concentrations of LREE with respect to the intermediate REE, the greatest degree of fractionation occurring between Sm and Nd. The

normalized REE patterns indicate that the Consort pegmatite garnets exhibit unusual REE concentrations. Nd and the lighter REE are depleted with respect to Sm and the other intermediate REE. Although the HREE-enriched patterns are produced by crystallochemical factors, the Sm/Nd ratio in these pegmatite garnets is unusually high (Schnetzler and Philpotts, 1970; Irving and Frey, 1978; Du Bray, 1988).

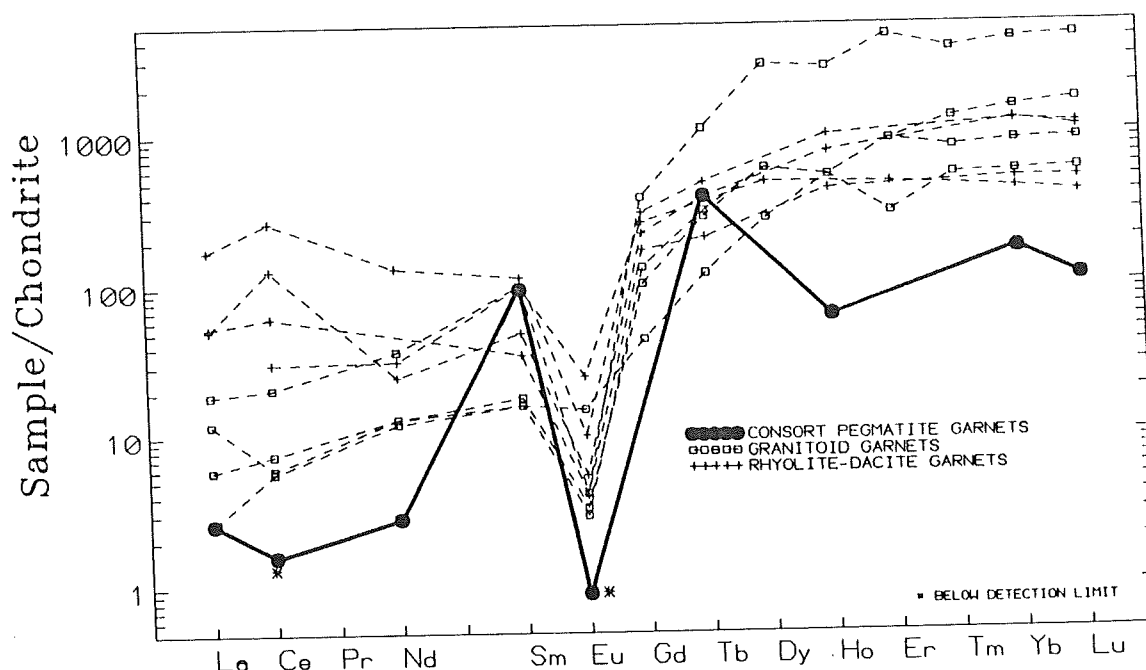


Figure 8: Rare-earth element patterns for igneous garnets compared to pegmatite garnets from the Consort pegmatites. REE patterns for comparison are from Du Bray (1988), Irving and Frey (1978) and Schnetzler and Philpotts (1970).

TABLE 5. REE analyses for garnets from pegmatites at the New Consort Gold Mines, Barberton greenstone belt

SAMPLE	50L	50/S1	50/L2	Average
La	0.45	0.44	1.02	0.64
Ce	BDL	BDL	BDL	-
Nd	BDL	BDL	BDL	BDL (1.30*)
Sm	12.5	23.54	7.82	14.62 (15.30*)
Eu	BDL	BDL	BDL	-
Tb	13.1	22.25	8.08	14.48
Ho	3.9	5.36	1.36	3.54
Yb	29.9	34.96	18.84	27.90
Lu	0.5	2.82	1.96	1.76

BDL:- Below detection limit

*:- Determined from isotope dilution

DISCUSSION

Pegmatite garnet Sm-Nd systematics

The REE patterns of garnets are controlled by several factors. Firstly, crystal structure and the laws of substitution dictate that the garnets are enriched in HREE with respect to LREE (Schnetzler and Philpotts, 1970; Irving and Frey, 1978; du Bray, 1988). Sm/Nd ratios for garnets are generally less than 1 but typically below 2. This is, however, not the case for the Consort pegmatite garnets which exhibit Sm/Nd ratios exceeding 10. The pronounced fractionation between Nd and Sm in the Consort pegmatite garnets is not normal, and suggests that crystallochemical effects alone probably cannot explain the unusually high Sm/Nd ratios. The Archaean age of the Consort pegmatites can explain the accumulation of radiogenic Nd, but not the extremely high Sm/Nd ratios. Consequently, it is suggested that these highly fractionated ratios are possibly the result of fluid interaction and REE mobilization within the pegmatites. Jahns and Burnham (1969) emphasized the role of water and/or other relatively volatile substances in the formation of pegmatites from a granitic magma. Under most conditions of pegmatite formation a separate fluid phase forms a dominant supercritical constituent. Thomas et al. (1988) who studied solid-liquid-vapour inclusions, have shown that CO₂ and dissolved salts are important additional components of the pegmatitic fluid phase. London (1986) examined various fluid inclusions within the Tanco pegmatite, Manitoba, showing that water or water+CO₂-bearing fluids evolved at a late stage from complex Li, B and F-rich fluids within the pegmatite. Volatile components such as F, B, P and Li have also been included in the evolution sequence of pegmatite formation (Černý, 1990). It is clear from these studies that pegmatites are characterized by a water-rich CO₂, salt, Li, B, P and F-bearing fluid phase that was an active chemical component of the system for protracted periods during and after their emplacement.

The mobility of the REEs under a variety of conditions during magmatic and post-magmatic conditions has been well established in the literature (Kosterin, 1959; Mineyev, 1963; Flynn and Burnham, 1978; Kerrich and Fryer, 1979; McLennan and Taylor, 1980; Muecke and Clarke, 1981; Taylor et al., 1981). Muecke and Clarke (1981), for example, have shown the importance of fluorine-enriched aqueous fluids on REE mobility in the late-magmatic stage of the South Mountain Batholith, Nova Scotia. The effectiveness of fluorine as a complexing ligand in the hydrothermal transport of REEs has also been demonstrated by Flynn and Burnham (1978). It has also been previously demonstrated that light and intermediate REEs are concentrated by Cl⁻-bearing fluids, while HREEs are concentrated by F⁻- and CO₃⁻²-bearing fluids (Taylor et al., 1981; McLennan and Taylor, 1980; Kosterin, 1959; Kerrich and Fryer, 1979; Flynn and Burnham, 1978). Similarly, some authors have shown preferential enrichment of the LREEs, intermediate REEs or the HREEs, causing kinked REE patterns (Alderton et al., 1980; Goad and Černý, 1981; Černý et al., 1987; Walker et al., 1986). With increased pH of hydrothermal solutions LREEs become increasingly mobile. The high solubility of simple NdCl₃ in hot water (Weast, 1982) also points to the selective mobilization of REEs, and unusual or kinked chondrite-normalized REE patterns.

Several forms of alteration associated with the Consort pegmatites have been noted through petrographic and geochemical evidence (Harris, 1992; Harris et al., 1993).

Alteration of the pegmatites was dominated by Na, K, Si and Li metasomatism which resulted in albitization, sericitization, silicification, holmquistite formation, biotite alteration and mica selvage growth. Tourmalinization is also seen on the edges of the pegmatites indicating the presence of boron-rich fluids. Constant whole-rock K/Rb ratios throughout zoned individual pegmatite bodies suggests that there has been fluid/melt equilibration at a late stage in the evolution of the pegmatites which has effectively served to homogenize various element ratios (Harris, 1992; Harris et al., 1993). Structural, mineralogical and geochemical evidence from the Consort pegmatites supports the fact that the alteration of the pegmatites occurred at a late stage of pegmatite formation, but still during the evolutionary path of the pegmatite system. These data suggest that fluid interaction in the Consort pegmatites was caused by late-stage crystallization fluids during the evolution of the Consort pegmatites, and was not due to a late unrelated fluid event.

In summary, the most suitable explanation for the extremely high Sm/Nd ratios in the Consort pegmatite garnets is thought to be due to selective REE complexing in a fluid phase. REE mobility and fractionation have been clearly demonstrated during fluid migration in several different environments. Fluids in the pegmatite environment appear to be capable of concentrating or depleting certain REEs with respect to one another. This is supported by the work of Whitworth (1992) who suggested that the spessartine-rich garnets from lithium pegmatites were formed by low pressure crystallization from a Li-H₂O-rich pegmatitic fluid. It is unlikely that the large spessartine component of the pegmatitic garnets could have been produced by partial melting (Whitworth, 1992). The present data suggests that an aqueous fluid, exsolved during pegmatite crystallization, complexed with Mn to form areas of high Mn concentrations, permitting spessartine-rich garnet formation.

Significance of ages from the Consort pegmatites

The Rb-Sr data of Allsopp et al. (1968) provided consistently younger ages than that of Harris (1992) and the present data. The exact reasons for this are unknown and may be coincidental. The Rb-Sr model ages obtained from the spodumene are young in comparison to the other age data from the Consort pegmatites (Tables 1 and 2) suggesting that the spodumene either has a low closure temperature or experienced a re-setting at ca. 2700 Ma. This disturbance may be correlated with the late-stage magmatism recorded by the Mpageni pluton at 2740 ± 15 Ma (Kamo et al., 1990), although it is uncertain as to why spodumene should be the only mineral exhibiting this disturbance. The large variation in Rb-Sr model ages from the muscovite separates also suggests some form of isotopic disturbance soon after pegmatite crystallization. Ages determined for the Consort pegmatites from Rb-Sr whole rock and the muscovite data vary between 2609 Ma and 3333 Ma. These variations may be due to subsolidus re-setting of the Rb-Sr isotopic system in the pegmatites. Figure 9 illustrates a histogram plot of all the available model age Rb-Sr and Sm-Nd data for the Consort pegmatites. An evaluation of the available isotopic data, including the Sm-Nd garnet model ages, indicates that the NCGM experienced a significant event at ca. 3040 Ma. The significance of this age is, however, difficult to interpret. It may represent either an intrusive age for the Consort pegmatites, or it may indicate the timing of deformation and alteration of the Consort pegmatites. Previous studies have shown that pegmatite emplacement at the NCGM was contemporaneous with deformation, and the alteration of these bodies is associated with late-stage evolution of the pegmatitic fluids (Harris, 1992;

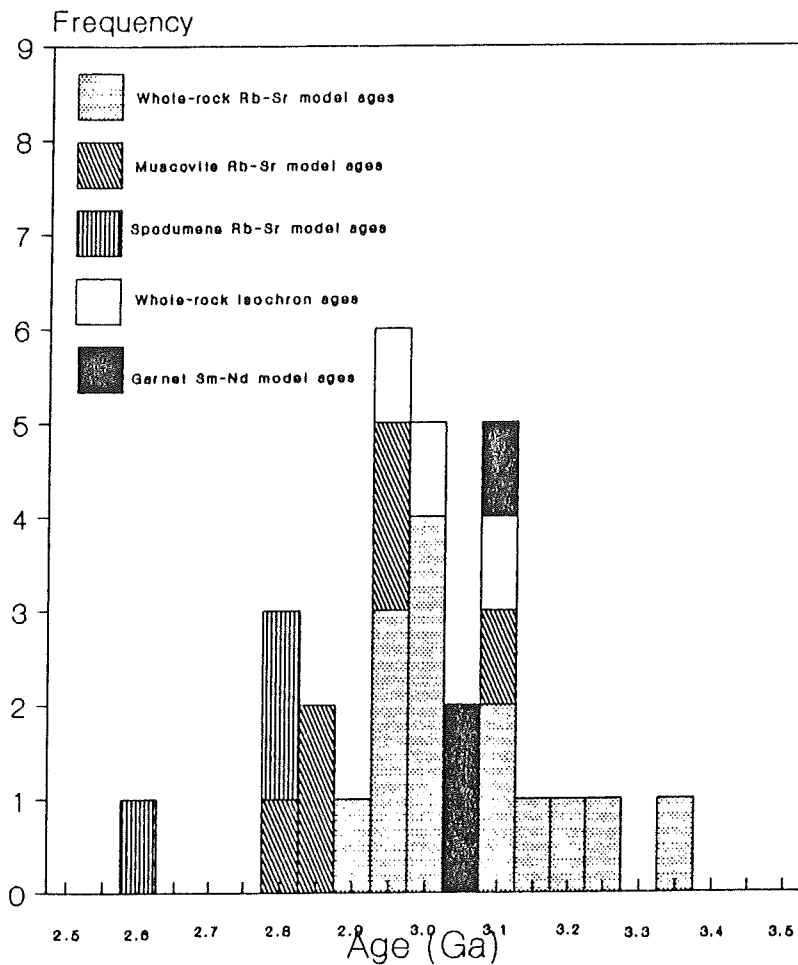


Figure 9: Histogram plot of all model age determinations for the Consort pegmatites (data from Allsopp et al., 1968, Harris, 1992, and this study).

Harris et al., 1993). Likewise, the unusual REE patterns in the Consort pegmatite garnets, which substantiate the 3040 Ma age, appear to be caused by late-stage crystallization fluids during the evolution of the Consort pegmatites. These lines of evidence suggest that the isotopic systems record a time soon after pegmatite emplacement.

The age of 3040 Ma also appears in the thermal record of the Kaap Valley Tonalite (KVT) where $^{40}\text{Ar}/^{39}\text{Ar}$ biotite ages at 3035 ± 9 Ma are recorded around the margin of the pluton (Layer et al., 1992). The marginal area of the KVT near the contact with the greenstone belt is also characterized by the presence of a foliation (Robb et al., 1986; Faure and Harris, 1991). The similarity of the age of the Consort pegmatites (≈ 3040 Ma) and the timing of $^{40}\text{Ar}/^{39}\text{Ar}$ biotite closure suggests that the deformation that is contemporaneous with the pegmatite intrusion also affected the margins of the KVT. Layer et al. (1992) have related the resetting of the biotite at the margin of the KVT to the thermal cooling of the Nelspruit Batholith. If this is correct then the Consort pegmatites must represent late-stage magmatism associated with the NB, the affects of which persisted for ± 60 Ma after its emplacement. However, an unexposed or, at present, unrecognized parental magma for the pegmatites, which exists somewhere beneath the NCGM, cannot be entirely ruled out.

As the pegmatites cross-cut the gold mineralization at the New Consort Gold Mines, they provide a minimum age constraint for the timing of gold mineralization in the area. This age broadly agrees with, but is structurally younger than, other constraints for gold mineralization in the BGB determined by U-Pb dating to be between 3126 ± 21 Ma and 3080 ± 18 Ma (De Ronde et al., 1991).

CONCLUSIONS

The extremely radiogenic isotope compositions of the Consort pegmatite garnets allow Sm-Nd model age determinations that are independent of uncertainties in the evolution of the reference reservoir (ie. CHUR or DM) or any crustal pre-history. While no REE concentrations for granitic pegmatite garnets have been reported, the major element chemistry of the garnets are not unusual with respect to pegmatite garnets. Preliminary work on garnets from pegmatites in the Mica area of the northeastern Transvaal, South Africa, also indicates similar extreme Sm/Nd ratios. These data suggest that similar Sm-Nd systematics may occur in garnets from other pegmatites on the Kaapvaal Craton. The high Sm/Nd ratio, which is due to fractionation of the LREEs with respect to the intermediate REEs, suggests REE mobility in fluid-rich systems late in the magmatic evolution of the rare-element pegmatites at the New Consort Gold Mines. The Rb-Sr and Sm-Nd isotope data provide an age of around 3040 Ma for the Consort pegmatites. This age is interpreted as representing a time soon after pegmatite emplacement, which is related to the Nelspruit Batholith event at ca. 3105 Ma, but which was re-set during deuteric fluid circulation and contemporaneous deformation of these bodies. Evidence from $^{40}\text{Ar}/^{39}\text{Ar}$ biotite ages on the margin of the KVT (Layer et al., 1992) suggests that the deformation associated with pegmatite intrusion at the NCGM is fairly extensive along the northern flank of the Barberton greenstone belt. Lastly, the Consort pegmatites cross-cut gold mineralization and therefore the Rb-Sr and Sm-Nd ages of ca. 3040 Ma provide a minimum age constraint for gold mineralization at the New Consort Gold Mines.

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