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Pb and Nd isotope constraints on the origin of high Mg and tholeiitic amphibolites, Kolar Schist Belt, South India

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Abstract. The late Archean, north-south trending Kolar Schist Belt in south India, 4 km wide by 80 km long, is thought to be a suture between two gneiss terranes (Krogstad et al. 1989). Within this volcanics-dominated belt are recognized both tholeiitic and high Mg (komatiitic and picritic) amphibolites, which make up some 70% and 5% respectively of the exposed outcrops. A massive tholeiitic amphibolite separates the belt into western and eastern parts. A Pb–Pb whole-rock age of 2732 ± 155 Ma on samples from a single outcrop of massive tholeiite is a minimum age for this rock. Samples of this rock have ε_{Nd} values at 2700 Ma that range between +3.8 and +6.8, μ_1 (initial $^{238}U/^{204}Pb$) of 7.5 and κ_1 (initial $^{232}Th/^{238}U$) of about 4. Two different types of high-Mg amphibolites are recognized from the western part of the belt: a picritic or P-type, and a komatiitic or K-type. The P-type have highly variable Ce/Al ratios all greater than chondritic, Nd/Yb ratios greater than chondritic, ε_{Nd} at 2700 Ma of +3.5 to +8.5 and Pb isotope compositions variable in $^{207}Pb/^{204}Pb$ with μ_1 about 8.0 and κ_1 of about 4. The trace-element data suggest that the light-REE enrichment is a character of the mantle source and is not due to residual garnet. The K-type amphibolites have near chondritic Ce/Al and Nd/Yb ratios, ε_{Nd} at 2700 Ma of +1.5 to +8, and μ_1 of about 8 and κ_1 of about 4. Although the P-type is light-REE enriched compared to the K-type, both types have similar Ce/Nd ratios as well as initial Pb and Nd isotopes. If the 2696 ± 136 Ma age for the Sm–Nd isochron which includes both types of high-Mg amphibolite has any significance it dates the time of light-REE enrichment of the mantle source for the P-type komatiitic amphibolites. The high-Mg amphibolites in the eastern part of the belt are light-REE enriched, have Pb isotopic compositions that are variable in $^{207}Pb/^{204}Pb$ with a μ_1 about 8.5 and ε_{Nd} at 2700 Ma of +1.8 to +4.5. Hydrothermal fluids associated with metamorphism and shearing prior to about 2400 Ma ago were responsible for the introduction of gold-quartz-carbonate veins into the Kolar Schist Belt. The Pb isotope composition of galena in these veins suggests that these fluids may have also introduced extraneous Pb from adjacent older granitoid gneisses into the amphibolites, which could be responsible for the variability in the $^{207}Pb/^{204}Pb$ ratios of the samples. This extraneous Pb probably is not responsible for the distinct Pb isotope character of each type of amphibolite.

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Introduction

The northeastern part of the south Indian Craton contains linear schist belts consisting of greenschist- to amphibolite-grade volcanics-dominated supracrustal rocks. These belts are surrounded by granites and gneisses collectively known as the Peninsular Gneisses. One of these belts is the north-south striking Kolar Schist Belt, which is 4 km wide by 80 km long (Fig. 1). The rocks of this belt were metamorphosed to middle- to upper-amphibolite grade (Rajamani et al. 1981). The southern end of the belt is about 40 km north of the transition to the granulite terrane found in the southern part of the Craton. Detailed descriptions of the geology of the belt are found in Narayanaswamy et al. (1960), Viswanatha and Ramakrishnan (1981), Granath and Rajamani (1982), and Balakrishnan and Rajamani (1987).

Previous studies of the Kolar amphibolites

The Kolar Schist Belt consists of tholeiitic amphibolites which cover about 70% of the area, high-Mg amphibolites, the banded-iron formation, and the Champion Gneiss (Fig. 1). Minor graphitic schist is interlayered with the amphibolites and iron formation. Preservation of rare-pillow structures and inter-layering of amphibolites with the banded iron formation suggest a submarine volcanic origin for some of the amphibolites.

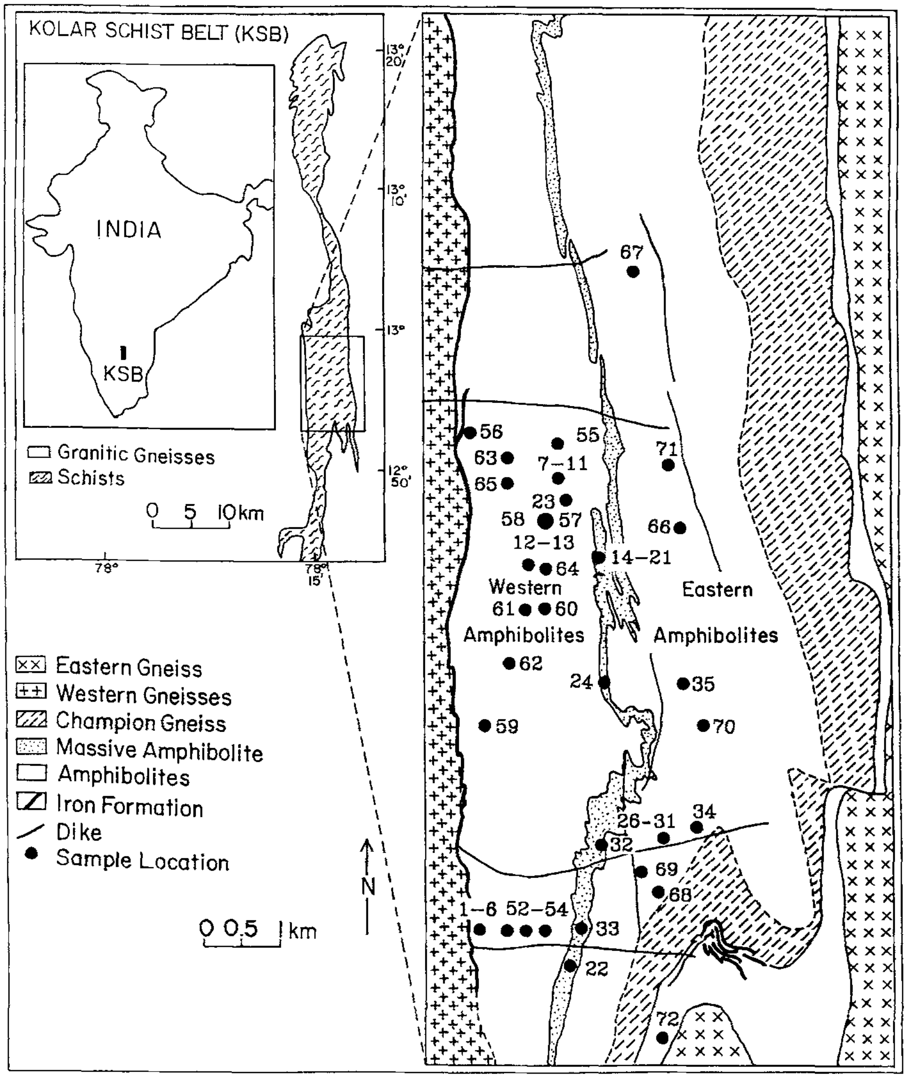

Fig. 1. Geological sketch map showing the location of samples for the central part of the Kolar Schist Belt based on the map of Viswanatha and Ramakrishnan (1981). The *eastern* and *western* parts of the belt are defined with respect to a band of massive tholeiitic amphibolites that occurs along the center of the belt

The amphibolites are classified into high-Mg and tholeiitic types based on their MgO contents, mineralogy and texture. High-Mg amphibolites usually have greater than 14 wt% MgO on hydrous basis (except their derivatives), rare plagioclase and two generations of amphiboles with different orientation and grain size (see Rajamani et al. 1981). The high-Mg amphibolites are fine to medium grained, make up 5–10% of the amphibolites and occur as units <10 m thick interlayered with tholeiitic amphibolites. The fine-grained variety could be flows whereas the relatively coarser type could be sills or dykes because of their homogeneous texture.

The tholeiitic amphibolites have less than 10 wt% MgO and consist of predominantly hornblende and plagioclase. They were subdivided further into three textural types: schistose, granular and massive. The massive variety is fine-grained, the least altered, and occurs as a continuous band along the central part of the belt (see Fig. 1) separating the belt into eastern and western parts. The schistose and granular varieties are medium grained and the degree of schistosity diminishes gradually from the former to the latter.

Rajamani et al. (1985) suggested that: (1) the high Mg amphibolites on the western part of the belt were derived from a light rare earth element (REE)-depleted source, whereas those on the eastern part of the belt were derived from light-REE-enriched sources; (2) both the western and eastern high Mg amphibolites represent low-per cent melts generated at about 50 kb as from mantle sources that had higher Fe/Mg ratios than pyrolite; (3) the parental magmas to the tholeiitic amphibolites on the western side were generated at pressures of less than 25 kbar from mantle sources that had much higher Fe/Mg ratios than did the sources for the high-Mg amphibolites (Rajamani et al. 1985, 1989).

Based on extensive data generated on high Mg amphibolites subsequently (Balakrishnan 1986) the western high Mg amphibolites are further subdivided into picritic (P-type) and komatiitic (K-type), both of which are similarly depleted in Ce–Nd relative to chondrites. However, relative to the heavy REE, the picritic variety is light REE enriched whereas the komatiitic variety is light REE depleted. There is a wide range in MgO abundances for the high Mg amphibolites. This can be seen in Fig. 2 where Ni is plotted against MgO wt% for high Mg amphibolites and possible derivatives.

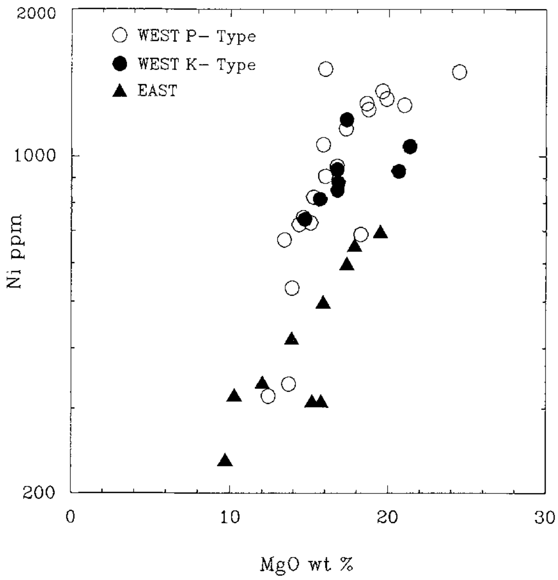

Fig. 2. Ni vs MgO for the high Mg amphibolites from the Kolar Schist Belt

Komatiites that are both light REE enriched (with or without Al depletion) and light REE depleted have also been reported as occurring together in the Abitibi and Kambalda greenstone belts (Arndt et al. 1977; Jahn et al. 1982). The light REE enrichment of the Newton Township komatiites in the Abitibi greenstone belt is attributed to assimilation of crustal material by light REE depleted komatiite magmas (Catell 1987). The light REE enriched komatiites of Kolar, however, seem to have been derived from light REE-enriched mantle sources (Rajamani et al. 1985; Balakrishnan et al. 1986 and 1988).

Thus, the 4-km-wide Kolar belt includes metavolcanics derived from mantle sources with significant differences in their Mg/Fe ratios and REE characteristics (Fig. 3), and generated over a large range of physical conditions. There is also a certain degree of geometric asymmetry in the distribution of various rock-types in the belt. The above features considered together with the data presented here point to the allochthonous nature of different types of amphibolites in the belt.

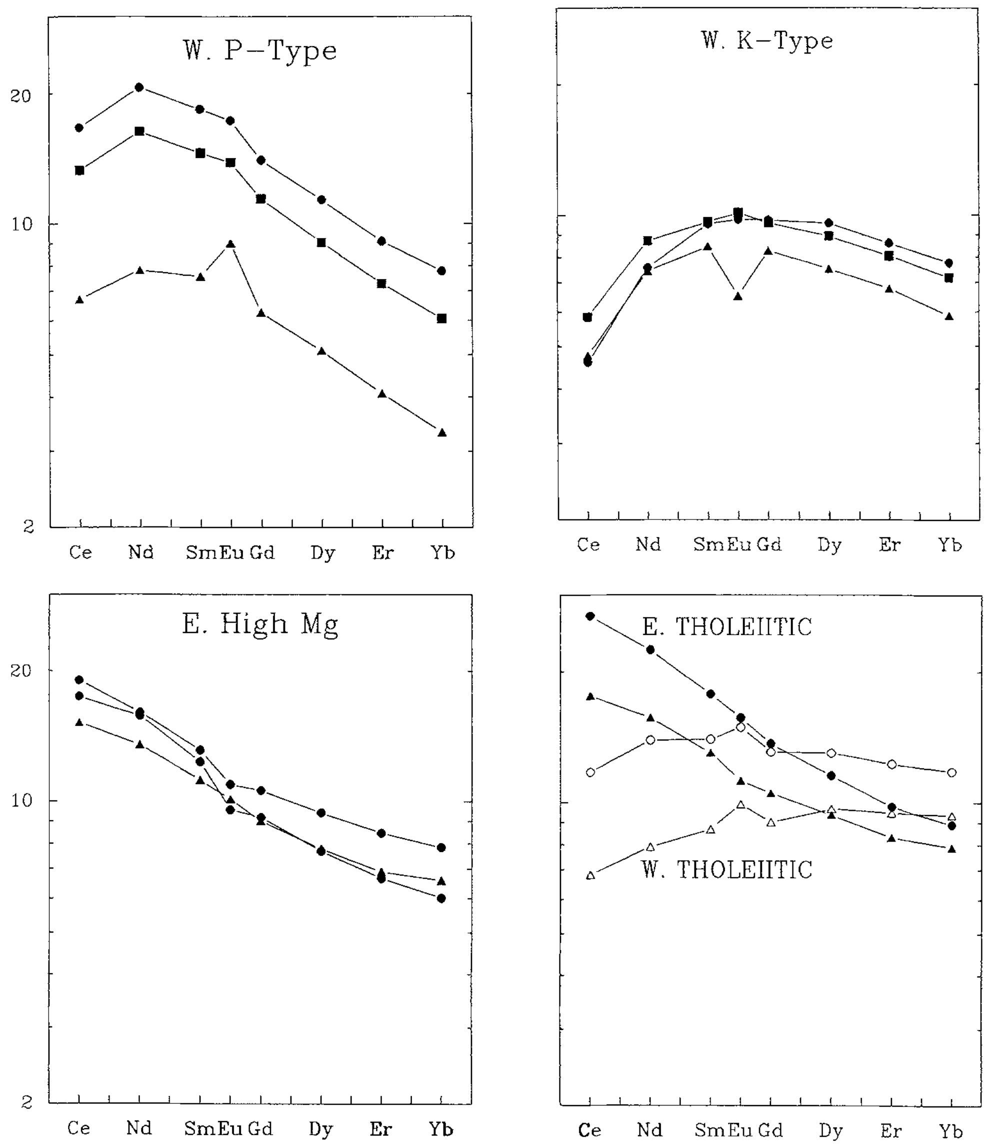

Fig. 3. Chondrite normalized rare-earth element patterns on selected samples from each of the five types of Kolar amphibolites. Data are from Balakrishnan (1986). The chondritic normalizing values are given in Hanson (1980). *Open symbols* = west tholeiitic; *closed symbols* = east tholeiitic

Geological context of the Kolar Schist Belt

Mukhopadhyay (1988) suggested that extensive horizontal E-W compression was responsible for recumbent isoclinal folding of the rocks of the belt and for the later shearing observed within and around the belt. The shear zones, up to 100 m wide, occur within as well as at the margins of the belt where the supracrustal rocks are in shear-contact with the surrounding gneisses. Within the belt the shear zones are the loci for gold-quartz-carbonate veins (Siva Siddaiah and Rajamani 1989).

Nd, Sr and Pb isotopic data combined with precise U–Pb ages on the granitoid gneisses in the study area show that the granitic gneisses east and west of the belt have different histories (Krogstad et al. 1989, in press). Although these gneisses were derived from sources with mantle-like isotopic characteristics between 2630 and 2530 Ma ago, the western granitoids were intrusive into an older basement (at least 3200 Ma old) while the eastern gneisses show no evidence for the presence of such older evolved crust (Krogstad et al. in press).

The schist belt was thought to have formed at about 2900 Ma ago on the basis of a Rb–Sr isochron in which samples of granitoid gneisses and rocks of the belt were included (Venkatasubramanian et al. 1971; Bhalla et al. 1978). As a result of our studies (see Krogstad et al. 1989) we know now that this isochron included rocks with different origins and histories. This age is not valid therefore. A goal of this study was to use Sm–Nd and Pb–Pb isochrons to date the amphibolites of the belt. Based on the results which we will discuss in this paper we suggest that the amphibolites were formed at about 2700 Ma.

An $^{40}Ar-^{39}Ar$ age of 2420 ± 12 Ma on muscovite developed in a sheared gneiss at the western margin of the belt dates the time of closure of muscovite for Ar and places a minimum on the time of shearing (Krogstad et al. 1988, 1989). K–Ar ages of 2260 and 2230 Ma on biotites from the amphibolites and pegmatites in the belt (Safonov et al. 1980) date the time of biotite closure for Ar when the area reached a temperature of about 300 to 350° C (Dodson and McClelland-Brown 1985).

Walker et al. (1989) suggested that extraneous, radiogenic Os and Sr and heavy O were introduced into the rocks of the belt at different periods. The extent of interaction of the rocks with invading fluids was highly variable. For example, a set of amphibolite samples from one outcrop plot on a 2700 Ma Rb–Sr isochron with an initial $^{87}Sr/^{86}Sr$ of 0.7015 indicating that the Rb–Sr system has not been disturbed for this set of rocks since 2700 Ma. Isotopic data for Pb on galenas from gold-quartz-carbonate veins in the amphibolites (Venkatasubramanian et al. 1977; Chernyshev et al. 1980) suggested that their Pb was derived in part from older, presumably crustal, sources with high U/Pb ratios.

Krogstad et al. (1989) concluded that the Kolar Schist Belt is a suture zone, along which at least four separate terranes have been brought together: the gneiss terranes on either side of the belt, and the light-REE-enriched and depleted amphibolitic terranes on the eastern and western sides of the Kolar Schist Belt.

Goals of this study

The goals of this study are to use the Sm–Nd and Pb–Pb isotope systems to discriminate among the different varieties of amphibolites of the Kolar Schist Belt, characterize the various mantle sources and compare them to other Archean sequences, and date the time of formation of the amphibolites.

Analytical methods

Amphibolite samples weighing about 10 kg were collected for geochemical studies. The high Mg amphibolites consist of actinolite, hornblende, and minor amounts of opaque minerals. A few samples of eastern high Mg amphibolites have in addition minor amounts of biotite and plagioclase. The tholeiitic amphibolites consist of hornblende, plagioclase and trace amounts of opaque minerals. Based on the successful Pb–Pb dating of high Mg rocks by Dupre et al. (1984), five to six samples were collected from individual outcrops of the different types of amphibolites for Pb isotopic analysis. Sample locations are shown in Fig. 1.

The samples were crushed by hand to a grain-size of less than 5 mm. About 100 g were then powdered in a hardened-tool steel mortar to a grain size of less than 0.18 mm. About 10 g of this powder was ground to <75 µm using an agate mortar and pestle. Aliquots of this powder were used for element and isotope analysis.

The rare-earth elements were determined by isotope dilution with an analytical uncertainty of less than 2% of the amount present. Sample dissolution for REE isotope dilution and Nd isotope composition analysis was carried out using $LiBO_2$ flux in high-purity graphite crucibles at 1050–1100° C. The detailed procedure is given in Vocke et al. (1987). Chemical separation for isotope dilution and isotope composition analysis for the first batch of samples was carried out using three column procedure: group separation of the REE using HNO_3 then HCl elutions on Dowex $50W \times 8$ resin, followed by methyllactic acid elution (Shirey and Hanson 1986). For subsequent batches the REE were co-precipitated with ferric hydroxides by adding NH_4OH to the fused-sample solution. After discarding the supernatent the precipitate was dissolved in 1N HCl and a group separation of REEs with HCl on $50W \times 8$ resin (Evans 1987). The REE were then separated on methyllactic acid. For the isotopic dilution analysis the REE were separated into four groups: Yb–Er; Gd; Eu–Nd; Ce.

For the Nd isotopic analysis 200 mg of sample which contained at least 1–2 micrograms of Nd were used. The total Nd blank was 1.7 ± 0.3 ng and the sample/blank ratios were over 1000, making a blank correction unnecessary. Isotope measurements for Nd were carried out on an NBS 30 cm-radius, 90° sector, solid-source mass spectrometer at Stony Brook. The sample Nd (about 10^{-6} g) was loaded as nitrate on Re side filaments.

The mass-spectrometer procedure used for Nd isotope-composition analysis is that of Shirey and Hanson (1986). The $^{143}Nd/^{144}Nd$ ratios measured were normalized to a $^{146}Nd/^{144}Nd$ ratio of 0.72190. For the initial analyses, based on the Nd standard runs of La Jolla Nd_2O_3, a correction (+0.000101) was applied to the data. Between September 1984 and April 1986 the electronics and vacuum system of the mass spectrometer were significantly upgraded. As a result, the later $^{143}Nd/^{144}Nd$ measurements made on the La Jolla Nd standard are different from those of earlier measurements. The mean of $^{143}Nd/^{144}Nd$ ratios made on the La Jolla Nd is 0.511850 ($n=26$) with two-sigma SD of the mean of 0.000006. No correction was applied for the data collected in this later period. Replicate analyses on samples carried out before and after the above changes that were made on the mass spectrometer agree within the stated analytical uncertainty (Table 1).

For Pb isotope analysis the whole-rock samples were first rinsed with 1N HCl. About 200 mg of sample was taken in a screw-capped PFA Teflon vial and digested with HF and HNO_3 overnight at 150° C. The solution with a few drops of H_2SO_4 was evaporated over a hot plate to complete dryness in order to break down insoluble fluorides. The residue was dissolved in 2N HCl and the solution split for isotope composition and isotope-dilution analysis. Separations of Pb, U and Th were carried out using Bio-Rad 1-X8 anion-exchange resin following $HCl-HBr-HNO_3$ chemistry (Manhès et al. 1984; Mezger et al. 1989).

The sample was loaded on a single Re filament as chloride using phosphoric acid and SiO_2 gel (Cameron et al. 1969). The runs were made at a source vacuum of less than 2×10^{-7} Torr and at 1200° C with a typical signal-intensity of about 1×10^{-11} A for $^{208}Pb^+$. The sample and standard runs were made under identical conditions. Based on repeated analyses of NBS Equal Atom Pb standard SRM 982, a mass-discrimination correction of $+0.10 \pm 0.02$% per AMU was applied to the sample ratios.

Table 1. Sm – Nd isotopic data for amphibolites from the Kolar Schist Belt

Map no.	Field no.	Sm[b]	Nd[b]	^{147}Sm/^{144}Nd	^{143}Nd/^{144}Nd[c]	eps.[d]	$f_{Sm/Nd}$[e]
				Western high-Mg amphibolites			
Picritic or P-type							
1	SB1-23	4.100	13.721	0.1807	[a]0.512597±16	4.8	0.0812
52	SB2-23	4.440	15.230	0.1763	0.512633± 7	7.1	0.1036
	replicate				0.512671±29		
53	SB3-23	4.053	14.302	0.1714	[a]0.512470±13	5.6	0.1286
	replicate				0.512494±22		
55	SB27-2	1.448	4.673	0.1875	[a]0.512698± 6	4.5	0.0470
	replicate				0.512690±26		
	replicate				0.512644±19		
61	SB3-26	2.195	8.663	0.1532	0.512065±24	4.0	0.2210
62	VR-14	1.627	5.223	0.1883	0.512918±20	8.5	0.0425
65	17-10	3.030	10.460	0.1752	[a]0.512444±10	3.8	0.1094
	replicate				0.512424±16		
Komatiitic or K-type							
54	SB7-23	1.752	4.328	0.2449	[a]0.513569± 7	1.5	0.2449
56	SB27-6	1.907	4.675	0.2467	0.513661±23	2.6	0.2541
57	SB29-2	1.849	5.203	0.2150	[a]0.513345±10	7.5	0.0931
	replicate				[a]0.513363±13		
58	SB29-1	1.622	4.426	0.2217	[a]0.513324±11	4.8	0.1270
	replicate				[a]0.513322±15		
59	SB4-25	1.181	3.438	0.2077	[a]0.512985±15	3.0	0.0562
60	SB1-26	1.740	4.280	0.2459	0.513867±19	6.9	0.2504
63	18-15	1.670	4.570	0.2210	[a]0.513376± 9	6.0	0.1238
	replicate				0.513379±22		
64	303	1.470	3.780	0.2352	[a]0.513478±10	3.0	0.1960
	replicate				0.513479±17		
				Eastern-high-Mg amphibolites			
66	K-3	2.291	8.630	0.1587	[a]0.512140±13	3.6	−0.1932
67	K-23	2.150	8.070	0.1611	[a]0.512098±11	1.9	−0.1809
	replicate				0.512100± 7		
33	22-7	1.820	5.970	0.1844	[a]0.512421± 8	0.1	−0.0630
68	SB1-28	2.365	9.399	0.1521	[a]0.512004± 7	3.2	0.2265
69	SB2-28	2.157	8.175	0.1596	[a]0.512165±10	3.7	0.1888
	replicate				0.512121±23		
70	SB1-4	2.270	8.650	0.1587	0.512155±18	3.8	0.1932
71	B1-83	2.518	9.574	0.1591	0.512059±19	1.8	0.1913
72	SB4-4	1.367	4.819	0.1715	0.512417±26	4.5	0.1281
				Western tholeiitic amphibolites			
24	16-8	1.680	4.750	0.2139	0.513134±21	3.8	0.0876
25	18-14	2.685	8.035	0.2021	[a]0.513081± 8	6.8	0.0276

The samples are located on Fig. 1 by the map no.

[a] Nd isotopic data obtained after upgrading of mass spectrometer, i.e., after April, 1986. Other samples were analyzed before mass spectrometer underwent modification. See discussion in Analytical methods

[b] Sm and Nd in ppm determined by isotope dilution

[c] In-run two sigma uncertainties for ^{143}Nd/^{144}Nd ratios

[d] Epsilon$_{Nd}$ at 2700 Ma calculated using CHUR values of 0.1967 and 0.512636 for ^{147}Sm/^{144}Nd and ^{143}Nd/^{144}Nd respectively

[e] $f_{Sm/Nd} = [(^{147}Sm/^{144}Nd_{sample}/^{147}Sm/^{144}Nd_{CHUR}) - 1]$

During this study the total procedural Pb blank was 260 to 487 pg, whereas the amount of Pb processed was always greater than 80 ng. Thus, the blank contribution is at most 0.6% of the sample Pb. The isotopic composition of the reagent blank is ^{206}Pb/^{204}Pb = 18.05, ^{207}Pb/^{204}Pb = 15.66 and ^{208}Pb/^{204}Pb = 37.86 (Krogstad 1988) which is very similar to the isotope-ratios for the samples. Thus a blank correction is insignificant.

The Sm – Nd and Pb isotope analytical data are presented in Tables 1 and 2, respectively.

Results

Compared to the western high Mg and tholeiitic amphibolites, the eastern amphibolites are enriched in the LILEs including the light REE (Fig. 3). The high Mg amphibolites from the western part of the belt are somewhat depleted in the heavy REE and variably depleted to enriched in the light REE (Fig. 3). Within the western

Table 2. Pb isotopic data for amphibolites from the Kolar Schist Belt

Map no.	Sample no.	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{207}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{204}Pb}$	Pb ppm
		Western high-Mg amphibolites			
Picritic or P-type					
1	SB1-23	14.968	15.106	34.667	
1	BOD 1	14.508	14.858	34.358	3.50
1	BOD 1 AW	16.511	15.362	38.407	
1	BOD 2	15.123	15.086	35.295	6.03
1	BOD 3	14.731	14.974	34.620	4.88
1	BOD 5	14.680	14.950	34.590	1.55
1	BOD 6	15.143	14.982	35.201	5.34
Komatiitic or K-type					
7	OGM 1	16.252	15.296	36.227	
7	OGM 2	16.260	15.260	35.588	10.46
7	OGM 3	15.774	15.250	35.745	0.41
7	OGM 4	15.299	15.139	35.026	1.31
7	OGM 6	15.575	15.089	35.784	0.40
12	RKOM 1	16.008	15.230	35.870	
12	RKOM 2	15.800	15.159	35.754	
		Western tholeiitic amphibolites			
14	T1	17.330	15.180	37.435	
14	T2	17.832	15.277	37.992	
14	T3	17.198	15.197	37.519	
14	T4	17.484	15.223	37.767	
14	T4 RES	17.206	15.169	37.739	
14	T5	18.335	15.373	38.576	
14	T5 RES	19.663	15.599	38.714	
14	T6	16.817	15.075	36.585	
22	T13579	20.107	15.715	38.565	
	replicate	20.099	15.713	38.580	
23	T18-14	16.300	15.022	35.000	
24	T16-8	17.797	15.404	35.867	
25	T20-8	16.428	15.193	36.375	
		Eastern high-Mg amphibolites			
31	EK 1	15.777	15.664	35.201	
31	EK 2	15.910	15.645	35.388	
31	EK 3	15.679	15.447	35.161	
31	EK 4	16.497	15.509	35.986	
31	EK 5	16.313	15.544	36.045	
31	EK 6	17.287	15.669	37.093	
		Eastern tholeiitic amphibolites			
32	ET 22-5	16.640	15.419	34.862	
33	ET 22-7	21.294	15.799	37.965	
34	ET 22-22	19.666	15.953	38.951	
35	SB20-1-1	19.952	16.078	39.574	1.74

Samples with the same Map no. were all taken from one outcrop at the location shown in Fig. 1. *AW* after a sample number means it is the acid wash from the leached sample. *RES* after a sample number means it is the residue of that sample after it was leached

high Mg amphibolites, there are two types of REE patterns. One is Ce-only depleted and heavy REE depleted. The other is depleted in Ce and Nd and less depleted in the heavy REEs. The closely associated tholeiitic amphibolites have patterns that are flat to slightly light REE depleted.

On a Ce vs Nd plot (Fig. 4), the eastern high Mg amphibolite samples lie above a line with a chondritic ratio, whereas the western high Mg amphibolite samples lie below the line. The relative enrichment of Ce–Nd of the eastern high Mg amphibolites cannot be explained by conditions of melting or fractional crystallization involving minerals with large distribution coefficients for the heavy REE. A suite of rocks related to a parental magma by different degrees of fractional crystallization of phases such as garnet would plot at an angle to a line representing Ce/Nd ratio of the parent (Arth and Hanson 1975). However, the eastern and western samples plot above and below the chondrite line respectively. This suggests that the light REE enrichment in the east-

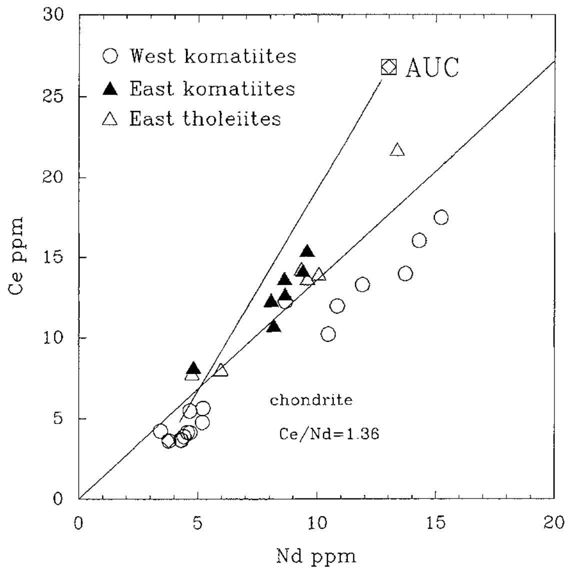

Fig. 4. Ce vs Nd abundances for the eastern and western high Mg amphibolites (*west and east komatiites, east tholeiites*) compared to a *line* with chondritic Ce/Nd ratio (1.36) and to a *mixing line* from one of the western high Mg samples to the composition of the average Archean upper crust, *AUC*, from Taylor and McLennan (1981). The granitoids adjacent to the Kolar Schist Belt plot on an *extension* of the mixing line. Essentially all of the western high Mg amphibolites plot *below* the chondrite line while the eastern high Mg amphibolites plot *above*. This consistent difference over a range of compositions implies that the mantle sources for the eastern and western high Mg suites also had distinct Ce/Nd ratios (Sun and Hanson 1975b).

ern high Mg amphibolites reflects the Ce/Nd ratio of their parental magmas or source which is greater than that for chondrites and and is not a result of fractional crystallization of originally chondritic or light REE depleted magmas.

If the magmas parental to the Kolar high Mg amphibolites have undergone crustal assimilation, the data should plot along a mixing line between light REE depleted high Mg magmas and the crustal contaminant in the Ce–Nd plot in Fig. 4 (cf. Horan et al. 1987). The consistency of the Ce/Nd ratios over a range in Ce and Nd abundances among the eastern high Mg samples suggests a higher Ce/Nd ratio for their source than that for chondrites. Rajamani et al. (1985) made a similar suggestion based on fewer data.

Among the high Mg amphibolites from the western part of the belt, there are two types: (1) the picritic or P-type which has a Sm/Nd ratio less than that for chondrites and are depleted in the heavy REE (Sm/Yb greater than 2) and (2) the komatiitic or K-type which is light-REE depleted have Sm/Nd greater than that for chondrites and is slightly depleted in the heavy REE (Sm/Yb greater than 1.4). The K-type amphibolites resemble Al-undepleted basaltic komatiites (Arndt et al. 1977), with CaO/Al_2O_3 ratios of about 0.8. The P-type amphibolites, however, have CaO/Al_2O_3 ratios 0.9–1.6 and CaO/TiO_2 ratios 6.5–11.2. Their REE and other geochemical features are comparable to those of the Al-depleted basaltic komatiites of the Barberton greenstone belt (Jahn et al. 1982) and of primitive picritic magmas (Krishnamurthy and Cox 1977; Cox and Hawkesworth 1985).

Ce and Al_2O_3 contents of high Mg rocks can provide information on the role of garnet in mantle magmatic processes. Because Ce is relatively incompatible in common upper mantle phases (Hanson 1980), its abundances in magmas are inversely proportional to the extent of melting. Although Al is incompatible in olivine-melt systems and slightly compatible in pyroxene-melt systems, it is an essential structural constituent of garnet. If garnet is present in the residue, the Al_2O_3 content of the melt is fixed by the garnet-melt distribution coefficient, K_d, independent of the amount of garnet present in the residue (Sun and Hanson 1975b). The garnet-melt K_d, however, will vary as a function of T and P.

For example, if we consider that the high Mg amphibolites are derived by melting of garnet peridotite at 50 kbar, a garnet-melt K_d for Al_2O_3 of about 4.4 would be expected, based on the experimental data of Takahashi (1986). Such a melt would have a maximum of 5.25 wt% Al_2O_3, because garnet has a maximum of about 23 wt% Al_2O_3. At lower pressures the Al_2O_3 contents of melts in equilibrium with garnet could be greater, because the garnet-melt K_d for Al_2O_3 is less, for example at 30 kbar the garnet-melt K_d for Al_2O_3 is about 2 (Takahashi 1986).

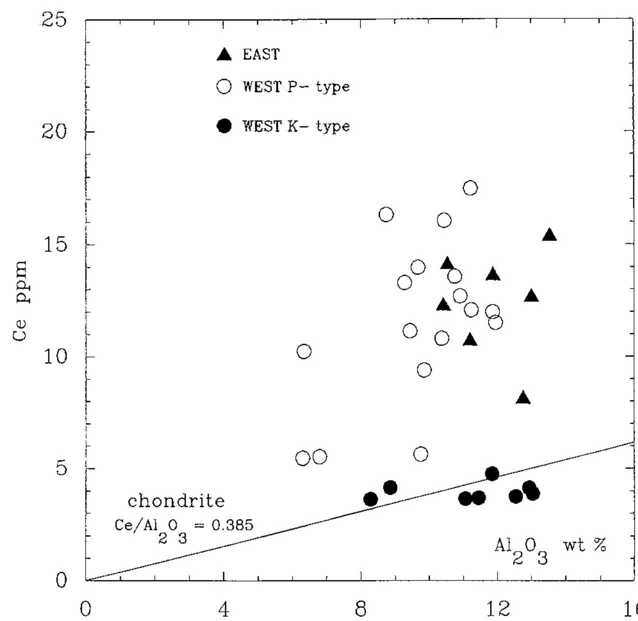

Fig. 5. Ce vs Al_2O_3 abundances of the high-Mg amphibolites from the Kolar Schist Belt compared to a *line* with chondritic ratio. The light REE depleted *K-type* (komatiitic) western high Mg amphibolites plot *near* the line with the chondritic ratio (0.385) suggesting that their magmas were derived from mantle sources with a Ce/Al_2O_3 ratio similar to that of chondrites. The P-type (picritic) western high Mg amphibolites show much scatter and lie well above the chondritic line. If garnet were in the residue and the sources had similar Ce/Al_2O_3 ratios, these data would require that the parental magmas were derived by different degrees of melting and at different depths in the mantle. If there was no garnet in the residue, as suggested by the Nd vs Yb plot (Fig. 6), the mantle sources were variably enriched in the light REE relative to Al_2O_3

Variation in Ce/Al_2O_3 among mantle-derived melts leaving garnet in residue could be due to different degrees of melting as well as different depths of melting. The K-type rocks have Ce/Al_2O_3 ratios (Fig. 5) similar to that for chondrites. If their parental magmas did not leave garnet in the residue, this would suggest that they originated from a source with near chondritic Ce/Al_2O_3 ratios.

The P-type high Mg amphibolites have a range in Ce and Al_2O_3 abundances and plot well above a line with a chondritic Ce/Al_2O_3 ratio (Fig. 5), suggesting that if garnet were in the residue their parental magmas were generated by variable degrees of melting of mantle sources over a range of pressures. If garnet were not left in the residue, this would imply that their sources had Ce/Al_2O_3 ratios higher than that of chondrites.

To test whether garnet was in the residue for either the P- or K-type amphibolites, Nd is plotted against Yb in Fig. 6. The P-type samples have a wide range in abundances of Nd and Yb and plot about a line which is nearly collinear with the origin, suggesting that Nd and Yb were equally incompatible and that their Nd/Yb ratio is that of their parental source. This suggests that either there was no garnet left in the residue or if there

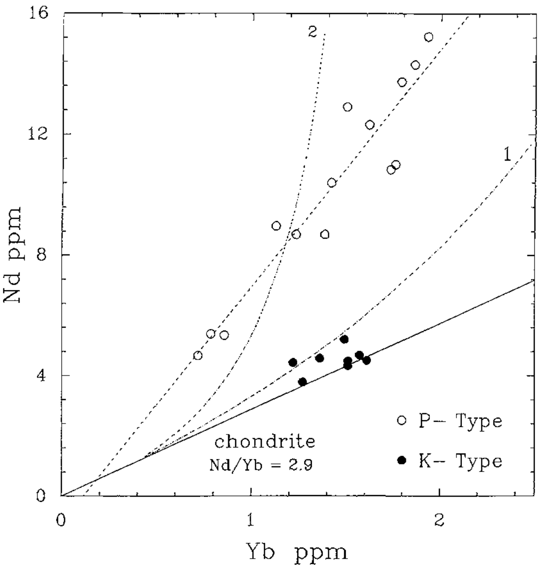

Fig. 6. Nd vs Yb abundances in the western *P-type* (picritic) and *K-type* (komatiitic) amphibolites compared to a *solid line* with a chondritic ratio (2.9). A regression line (*dashed*) through the P-type high-Mg amphibolites is nearly collinear with the origin suggesting that the heavy REE fractionation in the P-type high-Mg amphibolites is not a result of garnet in the residue. To show this *lines 1* and *2* are the paths of melts formed by 5 to 90% melting of a mantle with Yb=0.416 and Nd=1.194 ppm leaving 1% and 5% garnet in the residue respectively, using the distribution coefficients from Table 2 in Hanson (1980). If garnet were in the residue, a curved path would be expected. A line through a sequence of these rocks would intersect the Yb axis at a high value (Sun and Hanson 1975b). This is not the case. The P- and K-type west high Mg amphibolites magmas cannot be related to each other by different degrees of melting or by leaving different amounts of garnet in the residue. The chondrite normalized REE patterns of the P- and K-type high Mg amphibolites (Fig. 3) therefore have the same shape as that of their sources at the time of melting

was, its contribution to the bulk D (weight fraction of garnet multiplied by the garnet-melt K_d) for Yb was very small. In either case the heavy REE depletion of the P-type high Mg amphibolites is not due to the presence of garnet during melting or fractional crystallization. We thus conclude that the REE patterns of the P- and K-type amphibolites are similar in shape to those of their sources and that there were two separate sources for these rock types.

Sm – Nd isotopic system

All three of the high Mg rock types from the Kolar Schist Belt are plotted on the Sm – Nd isochron in Fig. 7. None of the three rock types has sufficient variation in $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ to give a meaningful age. A regression line through only the P- and K-types of the western high Mg amphibolites has a slope corresponding to an age of 2696 ± 136 Ma (1 SD). The six samples of the eastern high Mg amphibolites have a limited range and plot below the best-fit line for the western high Mg samples. The Sm – Nd whole rock isochron age for the western high Mg samples probably does not represent the time of their melting or crystallization. If the light REE enriched source of the P-type rocks resulting from enrichment of the K-type source in light REE, and the enriching component had the same Nd isotope ratio as did the K-type source, then the isochron may date the time of that light REE enrichment. Otherwise the isochron is a line without age significance connecting two sets of rock with different histories.

The high Mg and tholeiitic samples from the Kolar Schist Belt are plotted on an $f_{Sm/Nd}$ vs ε_{Nd} diagram in Fig. 8 ($f_{Sm/Nd}$ defined in Table 1). The LILE enrichment of mantle sources for the P-type amphibolites and the formation of massive tholeiitic amphibolites (see the following Pb – Pb section) probably occurred at about 2700 Ma and therefore the ε_{Nd} values were calculated for this age. Both the P- and K-type western high-Mg amphibolites show a large variation in ε_{Nd} values and have high positive values of ε_{Nd} at 2700 Ma, +1.5 to +8.5. For comparison, values for the older basement to the western gneisses are also plotted in Fig. 8. The lack of a trend in the data toward the older gneisses suggests that the variations in ε_{Nd} for the western high Mg amphibolites is not a result of contamination by the older crust.

Any variations in the Sm/Nd systematics from 2700 Ma, the possible time of origin, to 2400 Ma, the time of late shearing and metamorphism, would not be able to generate this range in ε_{Nd} (see Fig. 7). Although alteration during metamorphism or shearing may change the overall abundances of REE, the adjacent REEs, e.g., Sm and Nd, will not be sufficiently fractionated (Vocke et al. 1987) to change the Sm/Nd. Furthermore, even a 10% variation in the Sm/Nd ratio cannot explain the variation in ε_{Nd} values at 2700 Ma in any one type of the amphibolites (Fig. 7) and therefore the variation is probably not a result of alteration. We know

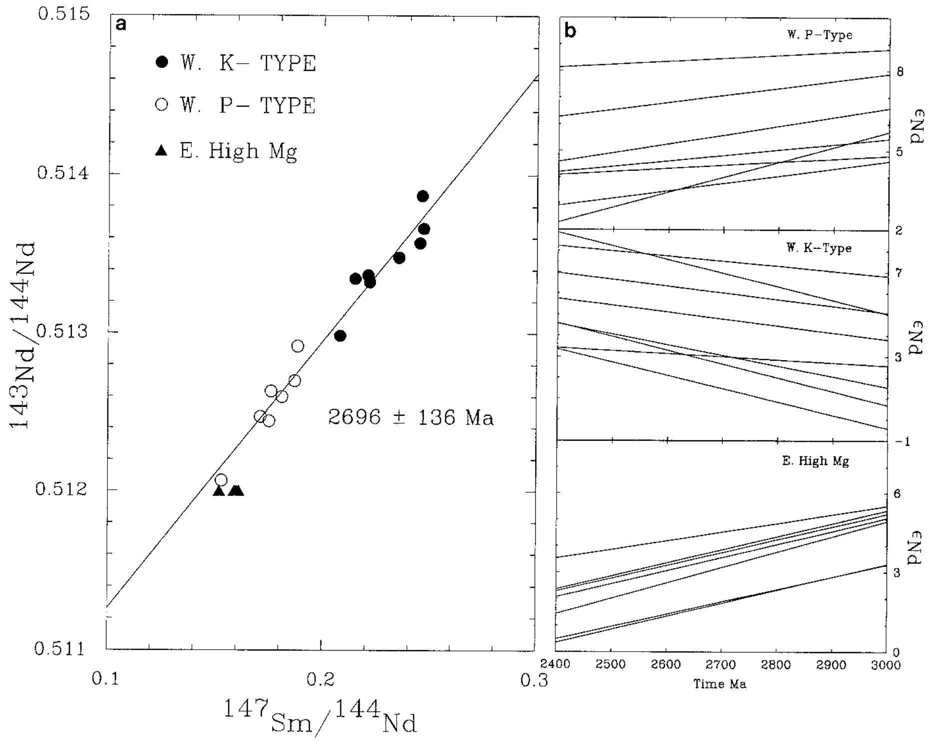

Fig. 7. **a** $^{143}Nd/^{144}Nd$ vs $^{147}Sm/^{144}Nd$ isochron plot of the high Mg amphibolites from the Kolar Schist Belt. Note that the *P-type* (picritic) and *K-type* (komatiitic) western high Mg amphibolites and the eastern high Mg amphibolites (*E. High Mg*) have distinct ranges in $^{147}Sm/^{144}Nd$ ratios. When the rock types are considered separately there is not enough spread to yield ages. A regression *line* including both the P- and K-type western high Mg amphibolites yields an age of 2696±136 Ma (1 SD from scatter) with an initial ratio of 0.50948 or ε_{Nd} +5.4. It is not clear that this age is meaningful. However, it may date the time of light REE enrichment of P-type sources. **b** ε_{Nd} vs time plot for the high Mg amphibolites plotted in **a**

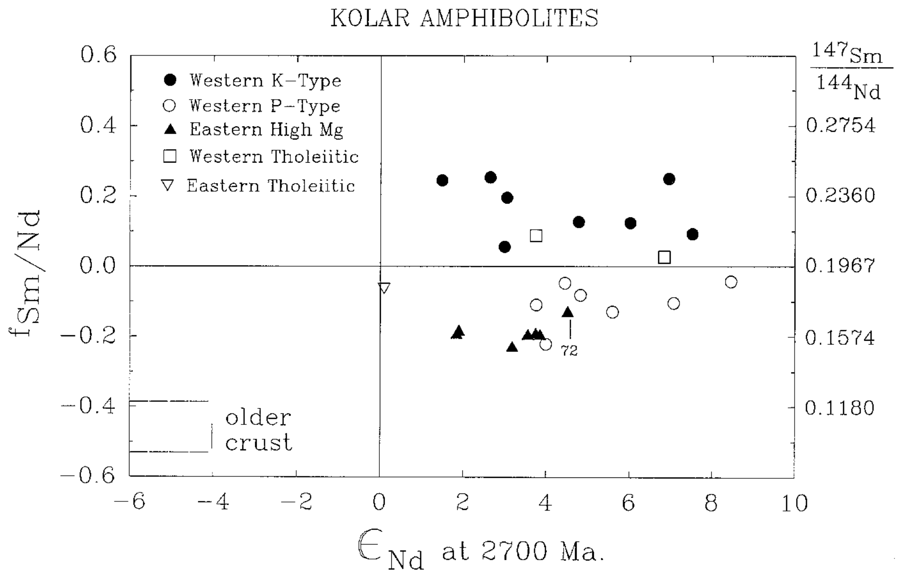

Fig. 8. $f_{Sm/Nd}$ vs ε_{Nd} plot (after Shirey and Hanson 1986) for the amphibolites from the Kolar Schist Belt. $f_{Sm/Nd} = [(^{147}Sm/^{144}Nd_{sample}/^{147}Sm/^{144}Nd_{CHUR}) - 1]$. In this diagram two component mixing is along a straight line. The *field* for the older basement (*older crust*) on the west side of the belt is also shown (Krogstad et al. in press). While the P- and K-type high Mg amphibolites from the western side of the belt have ranges in ε_{Nd} values, there is no trend suggesting contamination by older crust for either set. The eastern high Mg amphibolites show a narrower range in both ε_{Nd} and $f_{Sm/Nd}$. They lie *closer toward* the older crust than do the western high Mg amphibolites, which leaves open the possibility that their source may have been similar to that of the western high Mg amphibolites, but was contaminated by an older crustal component. No. 72 is a sample collected from close to the eastern contact with the granitoid gneisses. The massive tholeiitic amphibolites from the center of the belt lie *within* the field of the western high Mg amphibolites

of no possible contaminant that would have a more positive ε_{Nd} value than +8.5 at 2700 Ma. We therefore must conclude that the variation in ε_{Nd} for the western high-Mg amphibolites represents source heterogeneity and that these sources were light-REE depleted for long periods of time prior to melting. This range in ε_{Nd} values is not unique. Variations in ε_{Nd} values of +2.7 to +8 are seen among the 2700 Ma old komatiitic basalts of Kambalda (Chauvel et al. 1985; Claoue-Long et al. 1984; McCulloch and Compston 1981).

The ε_{Nd} values at 2700 Ma for the eastern high Mg rocks range from +1.8 to +4.5. This range is comparable to the komatiitic rocks reported from Alexo and Munro, Abitibi greenstone belt (Dupre et al. 1984;

Walker et al. 1988). Positive ε_{Nd} values and higher LILE abundances in the eastern high Mg amphibolites (Fig. 8) suggest that their sources had been depleted in light REE and were enriched in LILE shortly before melting. Five samples of the eastern high Mg amphibolites show a slight positive correlation between $f_{Sm/Nd}$ and ε_{Nd} in Fig. 8. This trend may indicate that the LILE enrichment was possibly a result of introduction of evolved older crust into the source region by subduction-related processes.

Two samples of central massive tholeiitic amphibolites have ε_{Nd} values of +3.8 and +6.8, values similar to those of the western high Mg amphibolites (Fig. 8).

The requirement of long-term variable depletion of light REE in the sources for the western high Mg amphibolites makes us wonder whether their sources could be Archean analogues to modern sources for mid-ocean ridge basalts. The sources for the eastern high Mg amphibolites do not show the same extent of long-term light REE depletion or variation in ε_{Nd}. Although the eastern high-Mg amphibolites are light REE enriched, their sources were depleted for a significant period of time prior to melting. The sources of the eastern high Mg amphibolites may have been enriched by introduction of older crustal components.

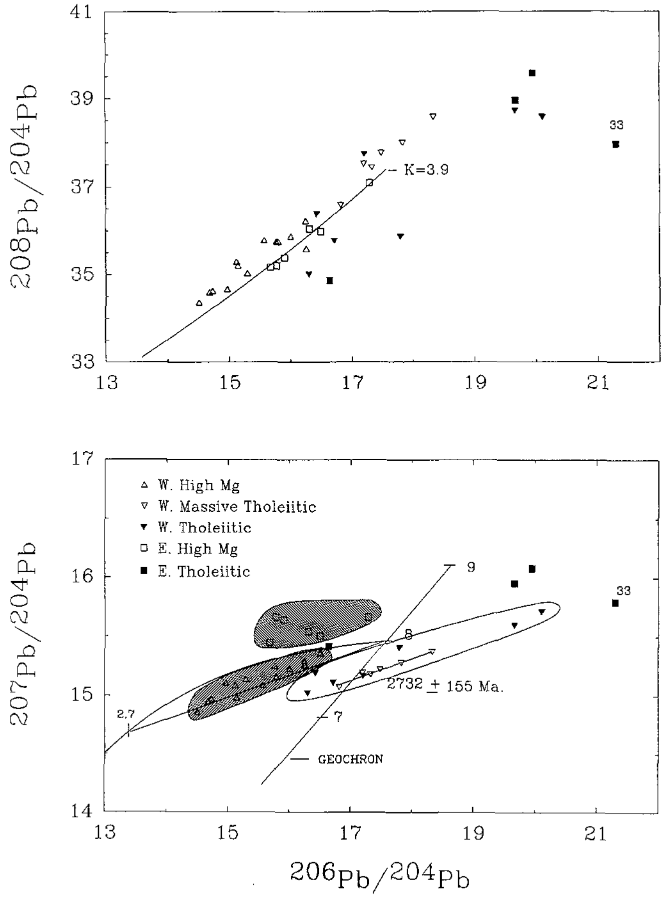

Fig. 9. $^{208}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ plot for amphibolites from the Kolar Schist Belt. The data on the $^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ plot are compared to a single stage $\mu=8$ *curve* and the *GEOCHRON*. Single stage μ values are plotted along the geochron. Six samples from a single outcrop of massive tholeiitic amphibolite from the center of the belt give an age of 2732 ± 155 Ma with a μ_1 of 7.51. The western high Mg amphibolites interlayered with tholeiitic amphibolites plot *above* the western and massive tholeiitic amphibolities, but show significant scatter. The samples of the western high Mg amphibolites with the lowest $^{207}Pb/^{204}Pb$ ratios have a μ_1 of about 8. The eastern high Mg amphibolites plot *well above* the $\mu=8$ curve and also show much scatter. Samples of the eastern high Mg amphibolites with the lowest $^{207}Pb/^{204}Pb$ ratios have μ_1 of about 8.5. The eastern and western high Mg amphibolites and the massive tholeiitic amphibolite from the center of the belt have $\kappa_1=3.8$ to 4.2. Some of the tholeiitic amphibolites have much lower κ_1 values suggesting Th loss or, more likely, U gain at the time of formation or shortly thereafter

Pb isotope data

Five to six samples were analyzed from each outcrop of P- and K-type western high Mg amphibolites, eastern high Mg amphibolite and central massive tholeiitic amphibolite. A few individual samples from other outcrops were also analyzed. The results are given in Table 2 and are shown in $^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ diagrams in Fig. 9. The data for each rock type is highly variable. Except for samples from an outcrop of the central massive tholeiitic amphibolite, the Pb isotope data cannot be used for dating.

Six samples from one outcrop of the central massive tholeiitic amphibolite in Fig. 9 lie tightly about a regression line with an age of 2732 ± 155 Ma, model II of York (1969). Two of the samples T4 and T5 were leached in 6N HNO_3 for 6 h and the leaches and residues were analyzed. The leaches had insufficient lead for isotopic analysis. The residue of sample T4 is less radiogenic, whereas the residue of sample T5 is more radiogenic than their unleached equivalents. Such variations may be a result of the non-uniform distribution of Pb and U in the samples. If we include these two analyses in the regression, the age is 2638 ± 100 Ma. Tholeiitic samples 13-5-79 and 18-14 from separate outcrops of the central massive tholeiitic amphibolite lie on an extension of this regression line. The data for the other varieties of tholeiitic amphibolite show much scatter.

The geologic significance of the Pb–Pb age of the central massive tholeiitic amphibolite depends on the process that caused variation in the Pb isotopic composition among samples collected within about 50 cm of each other. The massive tholeiitic amphibolite is fine-grained, least-altered, and mineralogically and chemically homogeneous so that the Pb isotopic system may not have been disturbed by later alteration or metamorphism. The variation in U/Pb may have been a result of separation of U and Pb during crystallization or due to hydrothermal alteration shortly after formation of the tholeiitic amphibolites (Brevart et al. 1981; Vidal and Clauer 1981; Dupre et al. 1984). The observed trend of these samples is not the result of mixing with lead from rocks in and around the Kolar Schist Belt, because any extraneous component should have had a much lower $^{207}Pb/^{204}Pb$ ratio than any Pb found in this area (see Fig. 10). Thus, the 2700 Ma Pb–Pb age represents a minimum

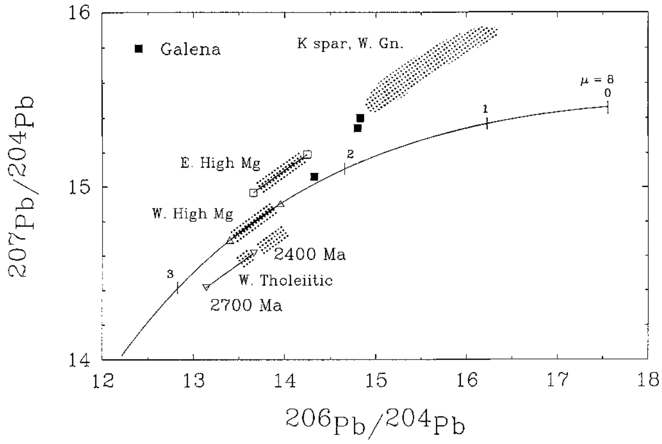

Fig. 10. $^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ plot showing the estimated positions at 2400 Ma of the western high-Mg (*W. High Mg*) eastern high-Mg (*E. High Mg*) and western (*W. Tholeiitic*) and central tholeiitic amphibolites; *galena* from gold-quartz-carbonate veins within the eastern amphibolites (Chernyshev et al. 1980, Venkatasubramanian 1977); and basement to the western gneisses represented by Pb compositions of leached potassium feldspar (*K spar, W. Gn.*) (Krogstad et al. 1989). The purpose of this plot is to evaluate the effect of introducing Pb into the amphibolites of the Kolar Schist Belt, which has an isotopic composition similar to that of the galena. The tholeiitic amphibolites at 2400 Ma would lie on an extension of a *chord* connecting 2700 Ma and 2400 Ma on a curve with μ_1 of 7.5. At 2400 Ma the western and eastern high-Mg amphibolites would lie along the 2700–2400 Ma chords for Pb growth curves of $\mu_1 = 8.0$ (*numbered curve*) and 8.5 respectively. We will assume that at about 2400 Ma hydrothermal fluids associated with metamorphism and shearing introduced Pb into the belt which is represented by the galena found in the Au-quartz veins. The galena plots *between* the amphibolites at 2400 Ma and the K-feldspar field, suggesting that it represents a mixture of these Pbs. The Pb in the western tholeiitic and high Mg amphibolites could have been variably enriched in $^{207}Pb/^{204}Pb$ by addition of Pb similar in isotope composition to that of galena Pb. The Pb in the eastern high Mg amphibolites could have obtained a higher or lower $^{207}Pb/^{204}Pb$ depending on whether the Pb added to the amphibolites was closer in composition to that of the K-feldspar or the western amphibolites

for the time of formation of the massive tholeiitic amphibolite.

If a single stage Pb isotopic evolution is assumed then the source for the massive tholeiitic amphibolites would have evolved with a $^{238}U/^{204}Pb_1$ (μ_1) ratio of 7.5 and $^{232}Th/^{238}U_1$ (κ_1) ratio of 4.0. Tholeiitic amphibolite samples from other outcrops have lower $^{208}Pb/^{204}Pb$ values although most plot on the 2700 Ma chord in Fig. 9. This suggests that at the time of melting their sources and magmas had similar uranogenic Pb isotopic ratios and that the lowered $^{208}Pb/^{204}Pb$ ratios are as a result of post-magmatic U addition. The same effect could not have been caused by loss of Th because the mobility of Th is negligible under amphibolite-grade metamorphism.

The western high-Mg amphibolites range in $^{206}Pb/^{204}Pb$ from 14.5–16.5 and even the samples from a single outcrop show significant scatter in $^{207}Pb/^{204}Pb$. This scatter cannot be attributed to source heterogeneity because samples from a single outcrop should have had the same initial Pb isotopic ratios. They, however, show the same amount of scatter as the whole data set.

Assimilation of crustal material may cause scatter in the Pb isotopic ratios in high Mg magmas. However, these high Mg amphibolites occur as units a few meters thick, are interlayered with tholeiitic amphibolites and do not overlie sediments. Furthermore the Ce/Nd ratios and ε_{Nd} values indicate that it is unlikely that the melts representing western high-Mg rocks could have assimilated long- or short-lived light REE enriched rocks. This would indicate that the Pb isotopic ratios were variably affected by extraneous Pb which did not affect the REE or Nd isotope systematics. The addition of Pb into the western high Mg amphibolites may be due to alteration associated with shearing and/or gold mineralization.

The western high Mg samples show less scatter in a plot of $^{208}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ ratios. Most of the samples plot close to but above the reference-curve with κ_1 of 3.9. All the western high Mg amphibolites plot below the $\mu_1 = 8$ reference-curve in a distinct field in Fig. 9. Possibly the $^{207}Pb/^{204}Pb$ ratio of the source for the western high Mg amphibolites was higher than that of the source for the western tholeiitic amphibolites and lower than those of the sources for the eastern high Mg amphibolites at the time of melting. Thus the sources for the western high Mg amphibolites had evolved with different μ-ratios from those of the closely associated tholeiitic amphibolites and eastern high Mg amphibolites.

Eastern high Mg samples from one outcrop also show significant scatter on the $^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ diagram and all of them plot above the reference curve for $\mu_1 = 8$ (Fig. 9). The scatter suggests that the eastern high Mg samples were affected by post magmatic alteration. However, their source could have had a higher $^{207}Pb/^{204}Pb$ ratio at 2700 Ma relative to the sources for the western tholeiitic and high-Mg rocks because they plot distinctly above the Pb growth curve for a μ_1 of 8.0. The higher initial $^{207}Pb/^{204}Pb$ ratios could have been a result of either long-term evolution with high U/Pb ratios or the introduction of extraneous radiogenic Pb into their sources. Thus the sources for the eastern high Mg amphibolites possibly had a different U–Pb history from that of the sources of the western high Mg amphibolites. The eastern high Mg amphibolites plot close to but below the curve of $\kappa_1 = 3.9$ in Fig. 9.

The occurrence of galena and Pb chlorides with the gold-quartz-carbonate veins (Siva Siddaiah and Rajamani 1989; Safonov et al. 1980) indicates that there was mobilization of Pb during shearing and ore formation. The relative positions of the inferred original Pb isotope ratios for the amphibolites and granitoid rocks at 2400 Ma is shown in Fig. 10. The Pb isotope ratios for the galenas plot between the values for the gneisses and the amphibolites suggesting that the Pb in the galena may be a mixture of Pb derived from the gneisses and amphibolites at about 2400 Ma.

If the Pb in the western tholeiitic amphibolites or high-Mg amphibolites were contaminated by the same

Pb which makes up the galena, their $^{207}Pb/^{204}Pb$ ratios would have been variably increased. Contamination of the Pb in the eastern high Mg amphibolites could have moved the Pb isotope composition toward lower or higher $^{207}Pb/^{204}Pb$ values. Thus the scatter in the Pb isotopic data of the amphibolites could be explained by the introduction at the time of shearing and gold-ore formation of Pb derived in part from the granitoid gneisses.

Discussion

Geochemical considerations suggest distinct mantle sources for the various amphibolites of the Kolar Schist Belt:

1. Within the high Mg amphibolites on the western side of the belt there are two distinct types, P-type (picritic) and K-type (komatiitic). Both types have similar Nd and Pb isotope compositions suggesting sources with long histories of light REE depletion ($\varepsilon_{Nd} = +1.5$ to $+8.5$ at 2700 Ma) and $\mu_1 =$ about 8 and $\kappa_1 =$ about 4.1 at 2700 Ma.
2. The eastern high Mg amphibolites were derived from sources with ε_{Nd} values of $+1.8$ to 4.5 and with $\mu_1 =$ about 8.5.
3. The massive tholeiitic amphibolites at the center of the belt were derived from sources with a long history of light REE depletion ($\varepsilon_{Nd} = +3.8$ and $+6.8$ at 2700 Ma) with $\mu_1 = 7.5$.

If the source of the P-type high Mg amphibolites from the western side of the Kolar Schist Belt was formed by enriching the K-type sources with LILE, then the enriching component had a similar Nd isotopic composition to that of the K-type high Mg amphibolite source. Such an enrichment would result in a reduction in $f_{Sm/Nd}$ without changing the ε_{Nd} values. In this case the Sm–Nd isochron age of 2700 Ma including both rock types dates the time of light REE enrichment of the P-type high Mg amphibolite sources. In any case the high positive ε_{Nd} values and the light REE enriched nature of the P-type high Mg amphibolite sources suggest that they were enriched in the light REE shortly before melting.

A review of ε_{Nd} values for Archean mantle derived rocks by Smith and Ludden (1989) indicates that most of the greenstone belts have rocks with variable ε_{Nd} values at the time of their formation (Onverwacht, Barberton; Talga-Talga, Pilbara Block; Norseman-Wiluna, Diemals-Marda, western Australia; Newton Township, Abitibi). The variation in Newton Township has been attributed to contamination of high Mg magmas by older crustal material (Catell 1987). However, the extensive variation in ε_{Nd} values for the western high Mg rocks from Kolar ($+1.5$ to $+8.5$), cannot be explained by crustal contamination (see Fig. 8 in which there is no correlation between ε_{Nd} and $f_{Sm/Nd}$). The variation most probably represents source heterogeneity.

The eastern high Mg amphibolite samples generally have lower ε_{Nd} values ($+1.8$ to $+4.5$), and some are weakly correlatable to $f_{Sm/Nd}$, suggesting that LILE enrichment of their sources might have included an input from evolved crustal material. This is consistent with their having higher $^{207}Pb/^{204}Pb$ ratios and lower κ_1 values than the other amphibolites (Fig. 9).

Supracrustal rocks of the Archean have dominantly positive epsilon$_{Nd}$ values requiring long term light REE depletion of their sources (Shirey and Hanson 1986). Growing evidence suggests that the komatiitic rocks from different greenstone belts, even within one craton, have variable ε_{Nd} values. This suggests that Archean mantle sources were heterogeneous in their Nd isotopic evolution.

Pb isotopic studies on the komatiitic rocks and associated magmatic sulfides from different greenstone belts also indicate heterogeneous evolution of the mantle sources during the Archean (Brevart et al. 1986). If we consider the initial Pb isotopic composition of the 2700 Ma-old komatiitic rocks discussed in Brevart et al. (1986) they have μ_1 values of 8.0 and 8.5 and κ_1 of 3 to 4.1. The calculated initial ratios for the three suites of high Mg rocks from the Kolar Schist Belt have μ_1 and κ_1 values that are similar to those for komatiitic rocks from other areas.

The massive tholeiitic amphibolites from the center of the Kolar Schist Belt have $\mu_1 = 7.5$ and $\kappa_1 = 4$, values which are similar to those for rocks of tholeiitic composition from 2700 Ma-greenstone belts of Superior Province (Wawa and Wabigoon belts) which have μ_1 values of 7.4 to 7.7 (Shirey and Carlson 1987).

The observed variations in the isotope composition of Pb, Nd and Sr and trace-element abundances in modern basalts erupted at different tectonic settings are attributed to differences in the isotopic compositions of their mantle sources (e.g., Sun 1980; Shirey et al. 1987). The parent/daughter ratios and the radiogenic isotopic ratios of Pb, Sr, and Nd indicate that their sources maintained geochemical differences for 1000 to 2500 Ma (Sun and Hanson 1975a; Sun 1980; Silver et al. 1988). The available data on Archean komatiitic rocks indicate that their mantle sources also had long-term differences in elemental ratios.

In the Kolar Schist Belt there are amphibolites derived from at least four distinct sources now occurring in a narrow, less than 4 km wide belt. The amphibolites derived from different sources also have geographic affinites: the high Mg rocks derived from Ce/Nd depleted sources occur on the western part, the high Mg rocks derived from light REE enriched sources occur in the eastern part of the belt and the massive tholeiitic amphibolites derived from sources with distinct Pb isotopic characteristics occur along the center of the belt.

It is not clear in which tectonic settings each of these amphibolites was developed. Rajamani et al. (1989) suggested that the tholeiitic amphibolites from the center of the belt were derived from lithospheric mantle, whereas the high-Mg amphibolites from the western part of the belt were derived at greater depths within the asthenosphere. The long-lived, light REE-depleted nature of the mantle source for the western high Mg amphibolites suggests that it might have been the Archean equivalent of the modern source for ocean-ridge basalts.

The light REE-enriched, high Mg amphibolites from the eastern part of the belt appear to have a separate mantle source from those of the western high Mg and tholeiitic amphibolites. The source for the eastern high Mg amphibolites may have been contaminated by older crustal components. It may be noted that the presence of an older continental crust is inferred within the gneissic terrane to west of the Kolar belt (Krogstad et al. 1989). However, if we see any evidence for crustal contamination of the sources, it is in the eastern amphibolites and not in the western amphibolites. This suggests that the amphibolites of the Kolar belt are allochthonous and were not spatially related at the time of their formation.

These tholeiitic and high Mg rocks formed from different mantle sources now occur in a suture zone where they were tectonically brought together with the gneisses on either side of the belt by 2400 Ma (Krogstad et al. 1988, 1989).

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