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Comparative Study of REE Distribution in Plutonic Rocks of Afif and Al Hijaz Terranes of the Arabian Shield

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ABSTRACT. Representative plutonic rock samples from Afif (19 samples) and Al-Hijaz (16 samples) were analyzed for their content of REE. The parameters of these REE were calculated and compared for the two terranes and ehondrite-normalized values plotted on various spider diagrams. LREE have a higher variation range than HREE. The sum of REE content is higher in Afif terrane than in Hijaz terrane. The gabbro-dioritic rocks in Afif terrane show more fractionation and enrichment. REE patterns for gabbro-dioritic rocks are different in the two terranes. This suggests different evolutionary mechanisms as well as differences in the composition of their parental magmas.

Introduction

Recent advances in understanding the systematics of abundance and distribution of rare earth elements (REE) in igneous rocks have primarily been used to study different petrogenetic aspects, such as magma source, processes involved in its generation and differentiation, as well as unravelling their paleo-tectonomagmatic settings. Post-consolidation changes accompanying metamorphism and/or alteration could also be revealed.

The object of this paper is to compare the REE data distribution in plutonic rocks with those of Afif and Al-Hijaz terranes of the Arabian Shield. The two terranes differ essentially in their tectonic setting; Afif is of continental origin and Al-Hijaz is of ensimatic island arc origin (Stoeser 1986). The studied samples also represent stages of the magmatic evolution of the Shield as well as a wide compositional range. The influence of these variations on the REE distribution patterns and their petrogenetic implications are discussed.

Geology and Sampling

Plutonic rocks in general constitute about 55% of the outcrop area of the Arabian Shield. While granites and granodiorites compose approximately 70% of these plutonic rocks, the rest includes tonalites and trondhjemites (20%), gabbros (8%) and syenites (2%). The evolution of these rocks was interpreted by Stoeser (1986) in terms of the classic "Wilson Cycle". Diorite, tonalitic, and trondhjemitic rocks were the dominant plutonic assemblage of the early phase of evolution (900-630 Ma). Geochemical variations in these rocks reflect a progressive change from primitive tholeiitic series to mature calc-alkaline series (Nassief *et al.* 1991). These rocks were formed in both ensimatic island arc and continental-marginal arc environments. This stage was followed by collision (660-610 Ma) between ensimatic arc terrane(s) and continental microplate(s) which resulted in a shift from arc-related magmatism to collision-related granitic magmatism. The final phase of plutonism (610-510 Ma) resulted in the formation of post-orogenic, intracratonic peraluminous to peralkaline alkali-feldspar granites. Rocks sampled in this study were collected from the Afif terrane of continental affinity and Al Hijaz terrane of ensimatic island arc affinity (Stoeser and Camp 1985) (Fig. 1). The continental affinity of Afif terrane is based on limited isotopic and geochemical evidences (Stoeser and Camp 1985). The island arc affinity of Al Hijaz terrane is more confirmly indicated as a result of a large number of isotopic and chemical data (Stoeser and Camp 1985, Vail 1985, Stacy and Agar 1985, and Stoeser 1986). REE data on the two terranes are rather limited.

The sampled rocks were classified according to their relationships with the layered volcano-sedimentary sequences. Rocks intruding the oldest layered rocks (or sequence A of Jackson and Ramsay 1980) were named by the authors stage I plutonites, those intruding the intermediate sequence B comprise stage II plutonites, and those intruding the upper sequence C comprise stage III plutonites. Table 1 gives the number of samples collected from the units of each stage and their distribution in Afif and Al-Hijaz terranes.

Although rocks of the three groups range in composition from diorite to granite with few gabbros, the relative abundance of these types varied significantly from one group to the other. Stage I plutonites are dominated by basic to intermediate rocks, whereas stages II and III are dominated by felsic granodiorites and granites.

Petrography

Although detailed petrographic description is given in various studies (Nassief *et al.* 1991, Nassief *et al.* 1992, and Nassief *et al.* 1993), the wide range in composition of the studied samples is shown on a Streckeisen diagram (Fig. 2). Although Afif samples follow more than one trend, no significant differences in mineral composition could be detected between rocks of the same type sampled in the two terranes. A possible exception is related to their accessory mineral content (Nassief *et al.* 1991). For example, allanite, sphene, and apatite are more abundant in granitoids of Afif terrane. Zircon and fluorite are more abundant in post-collision granitoids (stage III plutonites) compared to earlier stages granitoids.

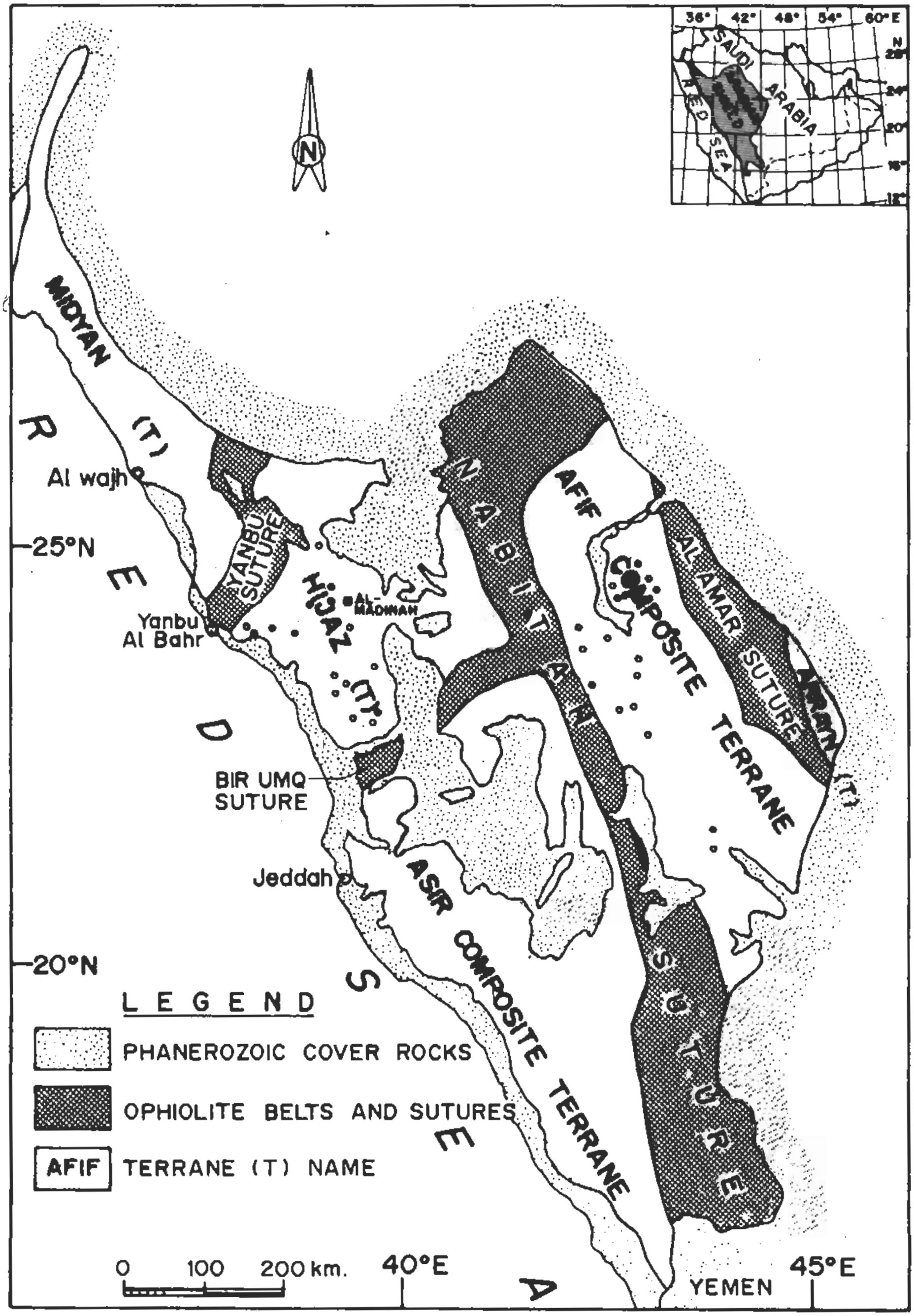
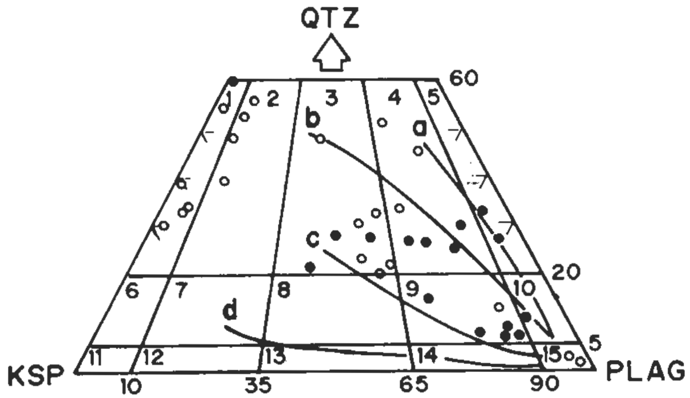


FIG. 1. Sketch map of the Arabian Shield showing the five terranes (modified after Stoeser and Camp 1984) and the approximate location of the samples (Open Circles).

TABLE 1. Distribution of studied samples according to stage, groups, and terranes.

Stage	Rock type	Terrane	
		Afif	Al Hijaz
I	granitoid	3	4
	gabbro-diorite	2	1
II	granitoid	4	4
	gabbro-diorite	1	1
III	granitoid	7	5
	gabbro-diorite	2	1



1. Alkali feldspar granite.
2. Syenogranite.
3. Monzogranite
4. Granodiorite.
5. Tonolite.
6. Alk. feldspar syenite.
7. Quartz syenite.
8. Quartz monzonite.
9. Quartz monzodiorite monzogabbro.
10. Quartz diorite, diorite gabbro.
11. Alk. feld. syenite.
12. Syenite.
13. Monozonite.
14. Monzodiorite.
15. Diorite gabbro.

FIG. 2. Model classification of Afif samples (○) and Al Hijaz samples (●), after Streckeisen (1976), showing trends modified after Lameyre and Bowden (1982).

Trends: a) Calc-alkaline – trondjemitic (low K)
b) Calc-alkalilne – granodioritic (medium K)
c) Calc-alkaline – monzonitic (high K)
d) Alkaline and peralkaline

Most sampled granites have biotite and/or hornblende as mafic minerals; few have muscovite. Selected samples are mostly fresh, but some show incipient alterations of biotite and hornblende to chlorite, feldspars to sericite, kaolinite, and the more calcic ones to epidote. In some cases, biotite includes secondary minerals in lensoid aggregates along cleavage planes.

Textures in the gabbroic rocks are well preserved and include cumulate and ophitic textures. In the felsic rocks, porphyritic textures were observed in a few cases. Cataclastic textures are uncommon, and are of local extent close to major faults where they form protomylonite with developed shear planes.

Analytical Technique

REE analyses were carried out at the Laboratories of the Geology Department of the Royal Holloway, Bedford New College of the University of London using the induced coupled plasma (ICP) technique following concentration by ion-exchange separation of REE. Working detection limits are approximately 1CA (chondrite abundance) for all REE except for Er and Pr where detection limits are 2CA and 10CA, respectively. Precision is in the range of 5-10%. Accuracy is better than 15%.

REE Systematics

The REE data are discussed first with respect to their absolute abundance and factors affecting their relative variations. This is followed by discussion of their chondrite normalised patterns and factors affecting REE fractionation. The petrogenetic aspects are then interpreted.

The REE data of the studied plutonic rocks are compared on the basis of their tectonic terrane affiliation (Afif or Hijaz) as well as their evolutionary stage. All granitoid rock samples have > 66% SiO_2, whereas all gabbro-diorite rock samples have < 56% SiO_2.

REE Abundance

A summary of the REE data (averages, ranges, and parameters) for 27 granitoid samples is presented in Table 2 and 3. The summary also includes some calculated fractionation parameters. The range of the total REE content is obviously wider in samples from the Afif terrane. The narrower range of Al Hijaz samples falls within Afif sample range, mostly close to the low concentration side. This feature is consistent in granitoids of the three evolutionary stages. Ranges of both terranes fall within the range of quartz-diorites, tonalites, granodiorites and trondhjemites (Σ REE = 10.5-499 ppm) reported by Birk *et al.* (1979). Wide ranges are to be expected in coarse-grained rocks due to large variations in both essential and accessory mineral proportions. A regular increase is noted in averages from stage I to stage III granitoids, except in Al Hijaz terrane where stage II samples have slightly lower values than stage I and stage III granitoids.

In general, light rare earth elements (LREE) have a wider variation range compared to heavy rare earth elements (HREE). Total REE content (Σ REE) is significantly higher for Afif terrane samples (average 147 ppm) compared to Al Hijaz terrane samples (average 89 ppm). This difference is most probably related to the higher abundance of REE-bearing minerals (allanite, apatite and sphene) in Afif terrane rocks. It is noted also that Σ LREE are 7-9 times higher than Σ HREE in both terranes and that variations in the absolute values of LREE are responsible for most of the variations in the studied rocks.

TABLE 2. Ranges and averages of REE parameters for granitoid rocks in Afif and Al Hijaz terranes.

Parameter	Stage	Afif		Al Hijaz	
		Range	Average	Range	Average
ΣREE	I	63.08 - 108.39	89.47	65.20 - 105.16	79.69
	II	57.85 - 177.61	113.68	53.64 - 98.95	75.22
	III	69.46 - 482.40	190.56	85.80 - 196.46	131.33
	All		146.93		89.18
ΣLREE	I	51.40 - 92.29	78.19	50.15 - 90.51	67.27
	II	53.21 - 166.29	102.19	49.25 - 82.25	63.90
	III	57.10 - 395.92	136.36	81.16 - 171.09	119.75
	All		114.58		83.64
ΣHREE	I	4.64 - 11.64	8.61	6.05 - 17.65	12.54
	II	4.64 - 23.34	11.37	4.39 - 16.69	11.34
	III	5.15 - 36.83	18.17	4.64 - 24.50	11.58
	All		12.72		11.82
$(Ce/Yb)_n$	I	2.68 - 13.36	8.05	2.30 - 5.41	3.82
	II	2.39 - 18.98	10.47	3.32 - 9.39	4.88
	III	2.93 - 26.46	8.61	6.59 - 21.25	12.97
	All		9.02		7.64
$(La/Lu)_n$	I	13.17 - 17.06	9.18	2.19 - 6.71	4.52
	II	4.25 - 21.56	11.77	4.32 - 4.58	6.07
	III	3.12 - 33.77	10.75	5.87 - 30.85	18.65
	All		10.84		10.43
$(Ce/Sm)_n$	I	2.17 - 8.60	4.60	1.39 - 3.45	2.37
	II	2.21 - 3.66	2.74	1.96 - 2.60	2.14
	III	1.61 - 6.33	2.90	2.82 - 3.66	3.28
	All		3.22		2.65
$(Dy/Yb)_n$	I	0.70 - 1.13	0.93	0.98 - 1.07	1.05
	II	1.02 - 1.81	1.47	1.12 - 1.32	1.20
	III	0.87 - 2.12	1.21	1.02 - 1.82	1.46
	All		1.22		1.25
Eu/Eu^*	I	0.63 - 1.48	0.94	0.67 - 0.93	0.75
	II	0.63 - 1.07	0.83	0.55 - 0.77	0.67
	III	0.07 - 0.54	0.26	0.42 - 0.82	0.67
	All		0.57		0.70

TABLE 3. REE parameters for granitoids in Afif and Al Hijaz terranes.

Level (stage)	Sample no.	Σ REE	$(Ce/Yb)_n$	$(La/Lu)_n$	$(Dy/Yb)_n$	$(Ce/Sm)_n$	Eu/Eu*	Eu/Sm
I	NA523	108.39	7.84	9.18	1.13	3.04	0.63	0.20
	NA536	96.93	13.63	17.06	0.70	8.60	1.48	0.45
	NA524	63.08	2.68	3.17	0.97	2.17	0.71	0.25
	NH225	84.74	2.30	2.19	1.09	1.39	0.67	0.25
	NA226	72.67	3.51	3.88	1.07	1.94	0.74	0.25
	NA257	105.16	4.05	5.29	1.04	2.68	0.67	0.23
	NA256	56.20	5.41	6.71	0.98	3.45	0.93	0.31
II	NA111	70.54	9.23	9.03	1.57	2.21	1.07	0.34
	NA514	57.85	11.28	12.24	1.48	2.76	0.96	0.30
	NA549	148.73	2.39	4.25	1.02	2.33	0.63	0.21
	NA107	177.61	18.98	21.56	1.81	3.66	0.66	0.20
	NH9	76.17	3.32	4.32	1.14	1.96	0.66	0.23
	NA6	72.10	3.38	4.58	1.12	2.05	0.69	0.23
	NA208	98.95	3.43	4.61	1.21	1.93	0.55	0.19
	NA66	53.64	9.39	10.76	1.32	2.60	0.77	0.23
III	NA24	482.40	26.46	33.77	2.12	3.29	0.26	0.07
	NA60	348.05	6.97	8.75	1.40	2.45	0.07	0.02
	NA20	89.90	12.95	17.33	1.08	2.67	0.54	0.16
	NA22	144.38	4.70	5.17	0.89	6.33	0.26	0.08
	NA27	82.85	3.04	3.31	0.87	2.23	0.29	0.09
	NA23	116.90	3.24	3.79	1.06	2.16	0.17	0.06
	NA6	69.46	2.93	3.12	1.02	1.61	0.23	0.07
	NH74	196.40	4.55	5.87	1.02	2.82	0.42	0.13
	NA201	146.36	6.59	8.66	1.25	2.91	0.72	0.23
	NA32	114.57	21.25	30.85	1.82	3.50	0.77	0.23
	NA36	85.80	19.39	28.86	1.78	3.66	0.82	0.24
	NA16	113.52	13.07	19.00	1.44	3.52	0.63	0.19

Similar trends are also noted in the data reported for 8 samples of gabbro-dioritic rocks in both terranes (Table 4). This table indicates that the REE abundances in gabbro-dioritic rocks of the Afif terrane shows a pronounced increase from stage I to stage III rocks. The content of Σ REE in stage III samples is eight times those in stage I. In Al Hijaz samples, REE concentrations are almost the same in two samples representing stage I and stage III, but in stage II the REE content generally falls significantly. This feature in stage II has been noted in granitoid rocks of the same terrane. Two samples representing stage I of Afif terrane have the lowest Σ REE in all the studied samples. The other 3 samples of Afif are generally higher in Σ REE content than the 3 samples of Al Hijaz.

REE Fractionation Patterns

It is well known that changes in the shapes of the REE patterns within a suite of

TABLE 4. REE parameters for gabbroic rocks in Afif and Al Hijaz terranes.

Terrane	Stage	Sample no.	ΣREE	$(Ce/Yb)_n$	$(La/Lu)_n$	$(Ce/Sm)_n$	$(Dy/Yb)_n$	Eu/Eu*	Eu/Sm
Afif		NA16	13.60	7.63	6.69	2.54	1.38	2.20	.69
	I	NA526	18.06	1.38	1.02	1.02	1.32	1.29	.52
	II	NA572	83.33	5.97	2.46	2.46	1.32	1.01	.35
	III	NA26	131.54	13.54	2.56	2.56	1.80	1.29	.39
		NA38	122.14	3.39	1.66	1.66	1.34	0.97	.34
Al Hijaz	I	NH250	69.14	3.61	3.80	1.56	1.46	1.11	.39
	II	NH101	47.85	2.77	2.86	1.63	1.26	1.10	.40
	III	NA73	70.08	2.39	2.55	1.43	1.21	0.98	.34

rocks is best evaluated by normalizing the concentration of individual REE in rocks to their abundance in chondritic meteorites (Nakamura 1974). Figure 3 shows the REE distribution patterns in all the studied samples of the two terranes. In these patterns it is obvious that variations in their shapes is essentially caused by variations in the absolute abundance of LREE. Also, the degree of LREE enrichment increases from stage I granitoids of both terranes through stage II to stage III. In general, most of the patterns displayed in Fig. 3 have rather moderate differentiation. Using the $(La/Lu)_n$ and $(Ce/Yb)_n$ ratios given in Table 3 as REE fractionation indices, it is noted that Afif samples show, in general, slightly more REE fractionation than in Al Hijaz samples. The latter samples show very regular increase in REE fractionation from the older granitoids to the younger. The close average values of $(La/Lu)_n$ ratios for all granitoids in both terranes (10.84 and 10.43), respectively, fall within the range of syenogranites (0.54 to 137) reported by Buma *et al.* (1971) and Condie (1978). One sample from stage I of each terrane shows apparently weak fractionation and almost flat profile in the HREE region.

Fractionation in LREE as indicated by the ratio $(Ce/Sm)_n$ is more pronounced in Afif samples (3.22) than in Al Hijaz (2.65). Afif granitoids have the highest values of LREE fractionation without pronounced change from older to younger stages. In Al Hijaz samples, on the other hand, LREE fractionation seems to increase from the older to the younger granitoids. $(Dy/Yb)_n$ ratios, as a reflection of HREE fractionation, are close to 1 in both terranes indicating weak HREE fractionation. Again, Al Hijaz samples show gradual increase in HREE fractionation from older to younger granitoids. Another characteristics is the noticeable concavity in the Dy-Yb region of some of Afif samples of stage I and stage III. Afif patterns are similar to the patterns of numerous granodiorites and granites of calc-alkaline association related both to subduction processes and collision events (Le Bell and La Val 1986) while Al Hijaz patterns are more similar to patterns in subduction related terranes (Wilson 1989).

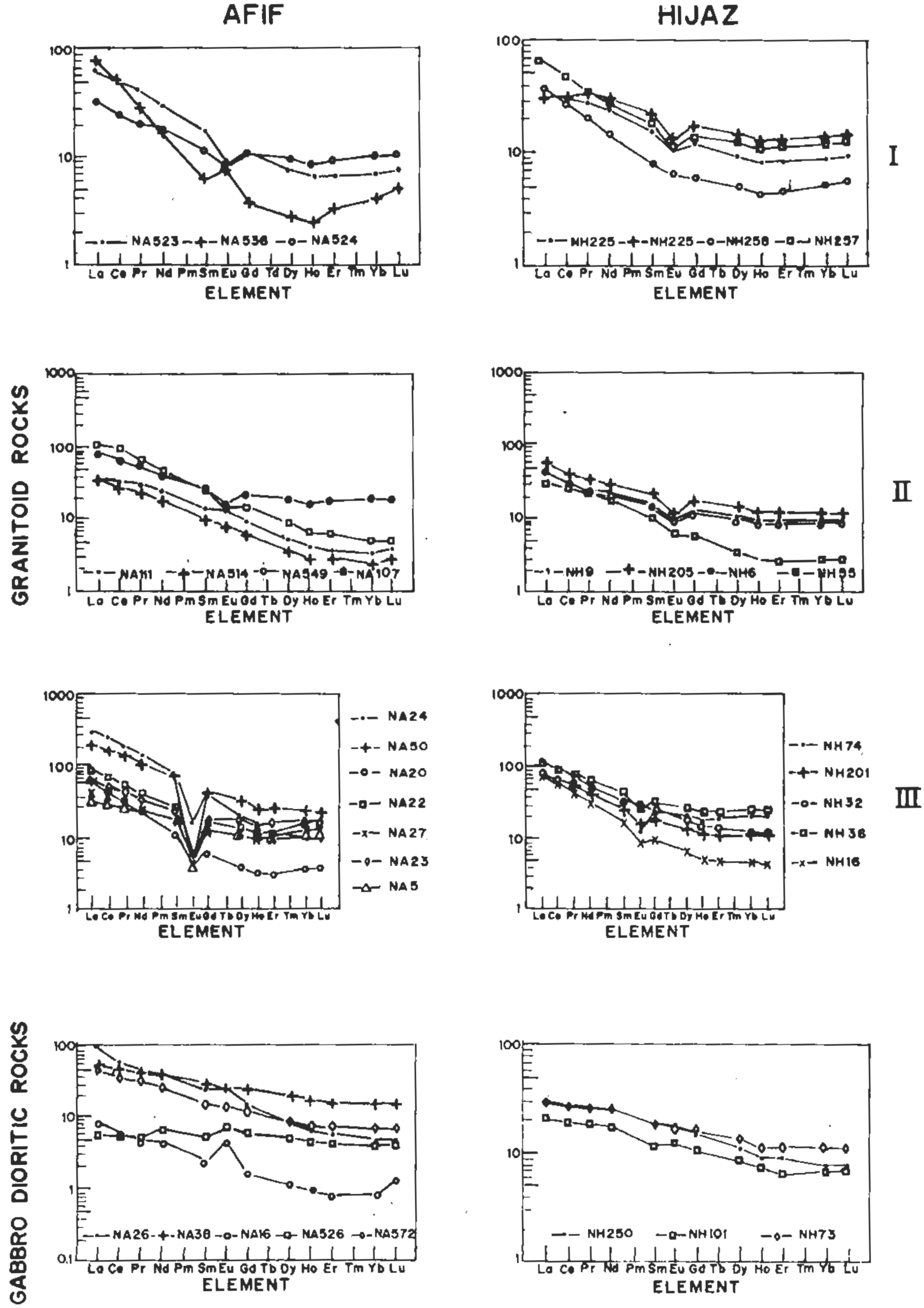


FIG. 3. REE pattern for granitoid and gabbro-dioritic rocks of Afif and Hijaz terranes.

Europium shows clear negative anomalies in most granitoids samples with five exceptions. Eu/Eu* ratio averages 0.57 for Afif samples and 0.70 for those of Al Hijaz, suggesting that plagioclase fractionation has played an important role in their evolution. Distinguishable increase of negative Eu anomalies from older to younger granitoids is observed in both terranes. REE patterns of stage III in Afif terrane have remarkable "sea gull" profiles, thus showing significant differences from those of Al Hijaz. Only one sample from stage I granitoids of Afif terrane has a REE pattern with moderate positive Eu anomaly, low REE content and large LREE/HREE ratio (17.06). This could have been produced by hornblende or perhaps garnet crystallization from less differentiated melts (Hunter *et al.* 1978). It is also noticed that the Eu anomaly increases in magnitude in the more felsic rocks in Al Hijaz terrane, while it is reversed in Afif terrane.

Slopes of REE patterns for gabbro-dioritic rocks (Fig. 3), as indication of fractionation, are characterised in Afif terrane by varying degrees of LREE enrichment relative to the HREE. The ratio $(La/Lu)_n$ ranges in Afif terrane from 21.91 in stage III to 1.45 in stage I. In Al Hijaz samples, the range of fractionation is 3.80 to 2.55. Fractionation of either LREE or HREE separately as indicated by $(Ce/Sm)_n$ and $(Dy/Yb)_n$, respectively, does not show that pronounced difference noted in the total fractionation $(La/Lu)_n$. The regular decrease in both $(Ce/Sm)_n$ and $(Dy/Yb)_n$ ratios in gabbro-dioritic rocks of Al Hijaz terrane from older to younger stages in exactly the reverse of the trend of the same ratios in granitoids. In Afif terrane, the irregularities in the REE patterns of the gabbro-dioritic rocks are the reverse of the irregularities of their corresponding granitoids.

Moderate positive Eu anomalies up to 2.2 in one gabbroic rocks of Afif terrane indicate that plagioclase accumulation has occurred, while the almost complete absence of Eu anomalies in Al Hijaz terrane clearly refers to the minor role of feldspar fractionation in the formation of the gabbroic samples.

Conclusion

The inverse relation of Eu anomalies between granitoids and gabbro-diorites, in general, suggests that the units are related and are probably differentiates of the same magma. REE are in general higher in samples of Afif terrane. This relative enrichment is most probably a function of the initial concentration of these elements in the source, and the degree of partial melting and subsequent fractional crystallisation. The previously detected continental affinity of Afif terrane is in favour of greater role for the "source" as a factor of enrichment. Lower degree of partial melting could also lead to REE enrichment but a realistic evaluation of such degree is beyond the scope of this study.

The more or less parallel REE patterns for different samples and the regular increase in REE from older to younger stages (except for Al Hijaz gabbro-diorites) also suggest that progressive differentiation by fractional crystallisation may have also played a role, as REE are incompatible and, therefore, they become increasingly concentrated in the more evolved sources. Fractionation of LREE is more pronounced in Afif samples. On the other hand, HREE fractionation is weak in both terranes. Europium shows clear negative anomalies in granitoid samples which are more pronounced in Afif terrane. This indicates that plagioclase fractionation played an important role in their evolution. Positive Eu anomalies in gabbro-dioritic samples exist only in Afif terrane samples probably as a result of plagioclase accumulation.

No conclusive decision could be reached concerning the tectonic environment for generation of the granitoids. Some patterns of Afif are similar to the patterns of numerous granodiorites and granites of calc-alkaline associations related to both subduction processes and collision events. The same is true for Al Hijaz patterns but closer similarity with subduction related granitoid patterns is noticeable. The shapes of the REE patterns for gabbro-rocks are different in the two terranes suggesting different evolution mechanisms.

The present work shows that selected plutonic rocks from the Afif and Al Hijaz terranes do have REE geochemical differences that can be interpreted in terms of their source and of their course of magmatic evolution.

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دراسة مقارنة لتوزيع العناصر الأرضية النادرة في الصخور الجوفية لأقليمي الحجاز وعفيف في الـــدرع العربي

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المستخلص . تم تحليل ١٩ عينة تمثل إقليم عفيف و ١٦ عينة تمثل إقليم الحجاز للتعرف على محتوى العناصر الأرضية النادرة في كل منهما . وجرى حساب ومقارنة النتائج البارامترية لكلا الإقليمين . وُقّعت النتائج على الرسوم البيانية الشعاعية . وجد أن العناصر الأرضية النادرة الخفيفة ذات معدل أكبر من العناصر النادرة الثقيلة . كما وجد أن مجموع محتوى العناصر الأرضية النادرة أكبر في إقليم عفيف حيث إن صخور الجابرو - ديورايت والتي بها أعلى إغناء تظهر تجزءاً أكبر مما تُظهره صخور إقليم الحجاز . وتُظهر الرسوم البيانية للعناصر الأرضية النـادرة لصخـور الجابرو - ديورايت في كلا الإقليمين تفاوتًا واضحًا مما يعكس اختلاف مصدرها ومسار الصهارة لكل منها .