

# Plagiogranites and gabbroic rocks from the Mingora ophiolitic mélange, Swat Valley, NW Frontier Province, Pakistan

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## Abstract

Major, trace element composition and Sr isotopic data were collected for gabbroic rocks, plagiogranites and albitites in the ophiolite assemblage from Swat Valley (NW Frontier Province, Pakistan). Petrographic study revealed that these rocks were subjected to important structural and mineralogical modifications due to greenschist-epidote-amphibolite facies sub-sea-floor metamorphism and to brecciation. On the other hand, the examination of whole rock chemical composition and of chemical trends showed that these rocks were affected by some chemical modifications, concerning especially Na<sub>2</sub>O, K<sub>2</sub>O and Rb. The very low contents of HFS (high field strength) and RE elements found in gabbroic rocks and plagiogranites were considered to be a primary magmatic feature pointing in part to their cumulitic nature and in part to an origin from a refractory parental magma. The Sr isotopic data indicate that gabbroic rocks and plagiogranites were subjected to exchange with sea water. The particular chemical features shared by gabbroic rocks and plagiogranites suggested that fractional crystallization was a possible evolution process. In contrast, albitites are characterized by anomalously high contents in HFSE and LREE and by values of the <sup>87</sup>Sr/<sup>86</sup>Sr ratio very close to sea water. These features suggest a more complex origin with respect to gabbroic rocks and plagiogranites.

**KEYWORDS:** plagiogranites, gabbroic rocks, albitites, ophiolites, Pakistan.

## Geological setting

OPHIOLITIC sequences crop out, in local areas, in the Swat Valley, namely in the zone affected by the principal tectonic feature known as Main Mantle Thrust (MMT) which marks the Suture Zone between Kohistan Island Arc and the Indo-Pakistan Plate (Fig. 1). The genesis of the magmatic rocks in the Kohistan Island Arc is linked to the subduction of the Tethys oceanic crust due to the northward movement of the Indo-Pakistan Plate. The Kohistan Island Arc, together

with slices of oceanic crust, was obducted onto the Indo-Pakistan Plate along the MMT (Tahirkheli *et al.*, 1979).

The Suture Zone is characterized by the presence of a tectonic mélange composed of magmatic and sedimentary terrains of oceanic origins and of blocks derived both from the Indo-Pakistan Plate (especially phyllites and rare augengneisses) and the Kohistan Island Arc (amphibolites and rare granulites).

According to Kazmi *et al.* (1984), in the Mingora-Shangla Pass area, from north to south,

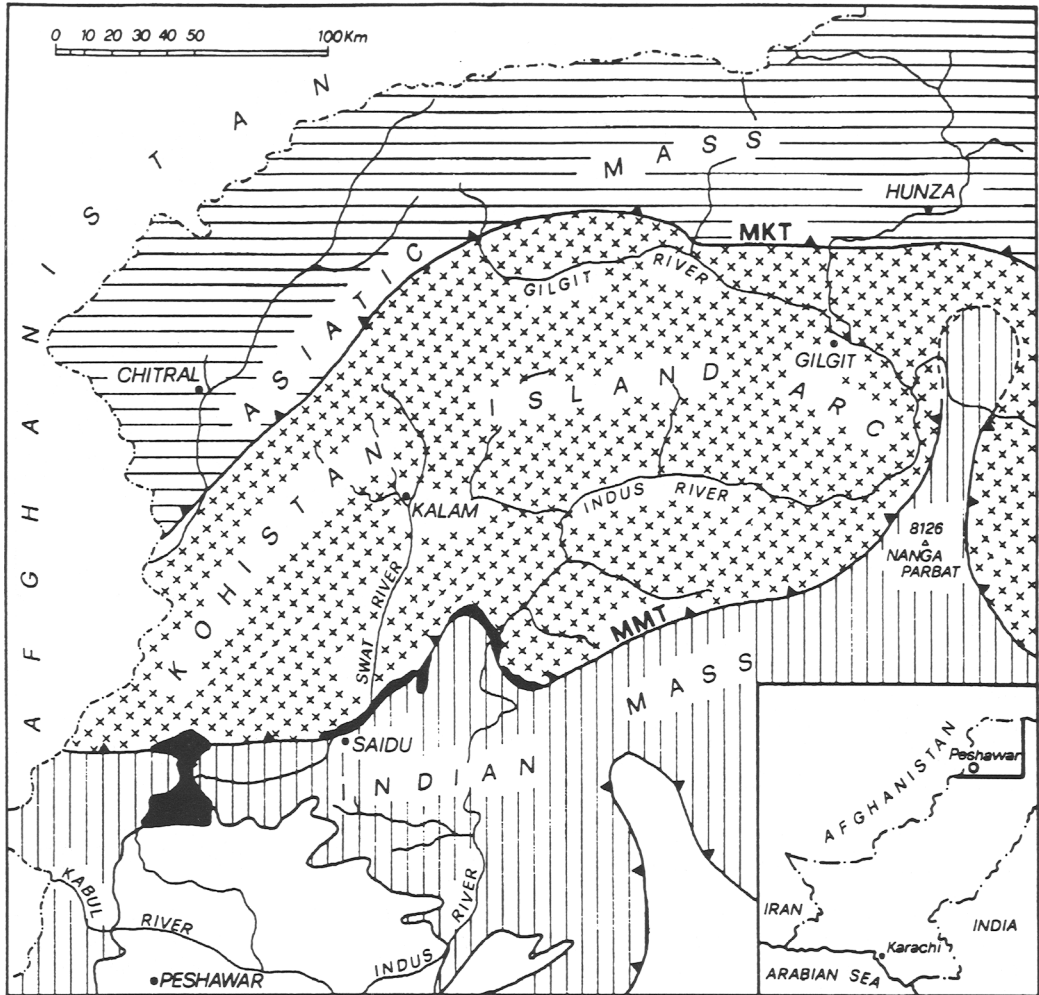


FIG. 1. Tectonic sketch map of the NW Pakistan. The Suture Zone is painted in black (after Tahirkheli, 1983).

the rocks of the Suture Zone can be subdivided into three 'units': the Shangla blueschist mélangé, the Charbagh greenschist mélangé, and the Mingora ophiolitic mélangé. The Shangla blueschist mélangé is characterized by the presence of crossite-bearing schists associated with metagabbros, serpentinites, phyllites, metagraywackes and marbles. In the latter, fossils of Jurassic to middle Cretaceous age occur (Kazmer *et al.*, 1983). Jan *et al.* (1981) indicate metamorphic *PT* conditions of approximately 7 kbar and 380°C, while Desio and Shams (1980) estimate by K–Ar method on muscovite an age of  $84 \pm 1.7$  m.y. (Upper Cretaceous: Turonian) for the blueschist metamorphism. In the opinion of Maluski and Matte (1984) the minimum age of the blueschist

metamorphism in the western part of Himalaya, on the basis of phengite data, is about 75–80 m.y. (Upper Cretaceous: Campanian). According to Tahirkheli (1983, pp 361–362), the collision between the Kohistan Island Arc and the Indo-Pakistan Plate took place "during post-Palaeocene, and subsequent suturing which created the Main Mantle Thrust occurred between Middle and Late Eocene". This interpretation is based on sedimentation and faunal evidence. The Charbagh greenschist mélangé is characterized by the occurrence of metabasalts, metapyroclastites and metasediments in the greenschist facies. The Mingora ophiolitic mélangé is composed of talc-dolomite schists, metabasalts, metapyroclastites, metagabbros,

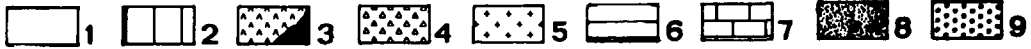
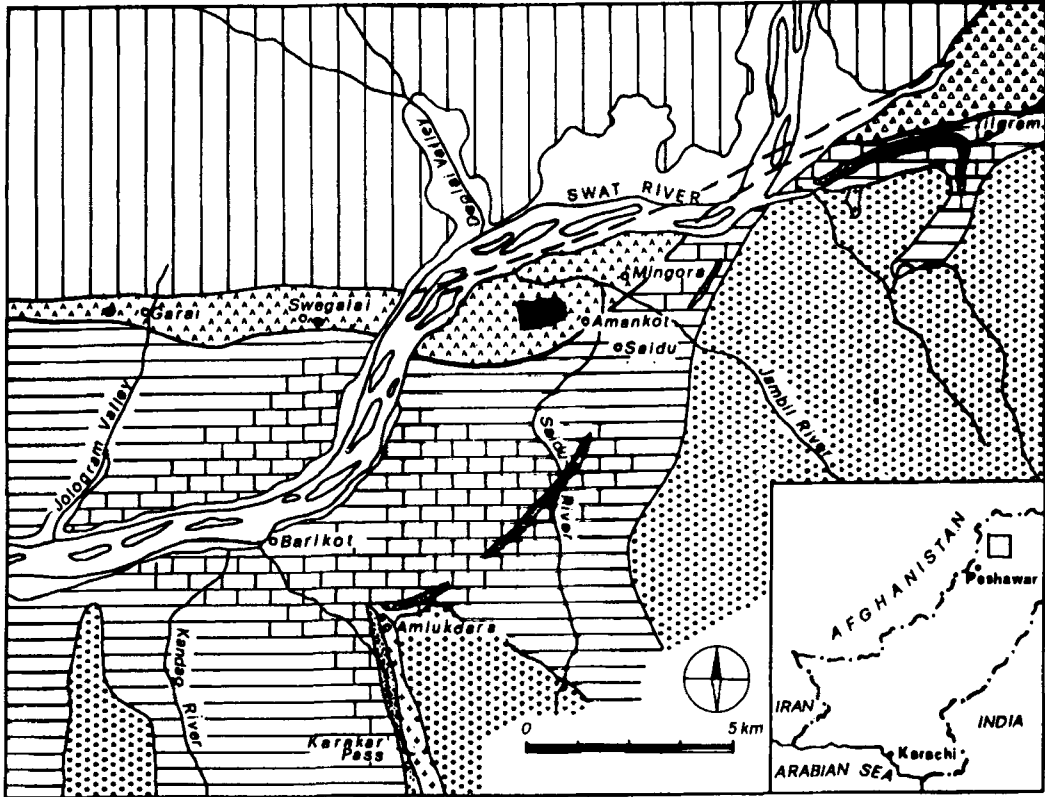


FIG. 2. Geological sketch map of the Lower Swat Valley. 1: Quaternary terrains. 2: Kohistan Island Arc. 3-4: Suture Zone. 3: soapstones with blocks and fragments of chlorite-schists, serpentine-schists, pillow lavas, limestones, jaspers; plagiogranites and gabbroic rocks are painted in black. 4: greenschists mélange and blueschists mélange. 5-9: Indo-Pakistan Plate. 5: tourmaline-granites (Karakar Pass) and granodiorites (Shakorai). 6: chloritoid-phylrites and garnet-kyanite-staurolite gneisses. 7: marbles. 8: amphibolites. 9: augengneisses and granitic gneisses.

Map compiled on the basis of the geological survey of S. Lorenzoni and E. Zanettin Lorenzoni (1989, 1990, 1991), C. Faccenna (1989), M. R. Di Florio (1990), P. Acquafredda (1991).

metasediments and metacherts. All these lithologies occur in a chaotic assemblage as blocks set in a matrix of talc-chlorite-dolomite-ankerite schists (soapstones). Three main features distinguish this mélange: 1) the abundance of ophiolite suite rocks; 2) the presence of talc-dolomite schists; and 3) the presence of emerald mineralization.

In the studied area (Fig. 2) the lithological association defined by Kazmi *et al.* (1984) as Mingora ophiolitic mélange can be recognized. Blueschists and greenschists crop out in the north-eastern part whereas in the Charbagh-Jologram Valley stretch of the Swat Valley the main lithology is represented by soapstone that often

bears fuchsite. On the basis of the high Sc, V, Cr, Mn, Co, Ni contents, Snee *et al.* (1989) suggested that soapstone derives from a deep transformation of the oceanic magmatic rocks. Random, ophiolite-derived blocks and fragments can be found within soapstone. They have a size ranging from 1 cm up to 100 m and include various ophiolitic rock types: chlorite-schists (sometimes with magnetite), sheared serpentinites, pillow lavas, limestones, jaspers, and carbonate-phylrites. These lithologies, except for chlorite-schists, can be observed chiefly down the Jologram Valley, to the west of Garai, on hill 3793 (Fig. 2). Furthermore, small quantities of massive rocks

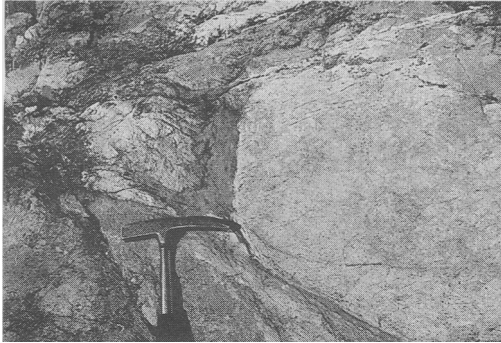


FIG. 3. Lenses and boudins of granular intrusive rocks (gabbroic rocks and plagiogranites) found within the chlorite-schists of the Mingora ophiolitic mélange.

showing magmatic granular texture, represented by gabbroic rocks, plagiogranites, aplites and albitites, have been recognized for the first time. These massive rocks crop out in three distinct zones: on the west side of Saidu River, above the village of Amankot; near Swegalai; and in the Jologram Valley to the west of Garai. Blocks of gabbroic rocks and plagiogranites have been also found in the Ugand Valley, near Tilgram village. Veins and dykes of plagiogranites, intruded in crossite-bearing schists, have been noted in the area of Shangla Pass (Q. M. Jan, Peshawar University, pers. comm.).

In this paper the rock types cropping out in the neighbourhood of Amankot and Swegalai have been investigated. Field relations between the various lithologies are extremely difficult to establish due to intensive shearing and brecciation. In these zones, the ophiolitic mélange consists of soapstones, chlorite-schists and talc-schists. Post-kinematic muscovite and tremolite occur in chlorite-schists and talc-schists. Lenses of gabbroic rocks, plagiogranites and albitites are enclosed in the ophiolitic mélange (Fig. 3). These lenses (20–30 m in length and 2–3 m in thickness) are oriented coherently with the schistosity of the host rock and sometimes exhibit irregular and jagged contours. Gabbroic rocks and plagiogranites have a greyish colour and can scarcely be distinguished in the field. A possible key useful for the distinction is the shape of amphibole, which is usually stubby in gabbroic rocks and needle-like in plagiogranites. In addition, a larger proportion of epidote occurs in gabbroic rocks. Albitites show the same features as the other magmatic rocks, except they have a lighter colour.

The principal aim of this paper is to define petrographic and geochemical features (including

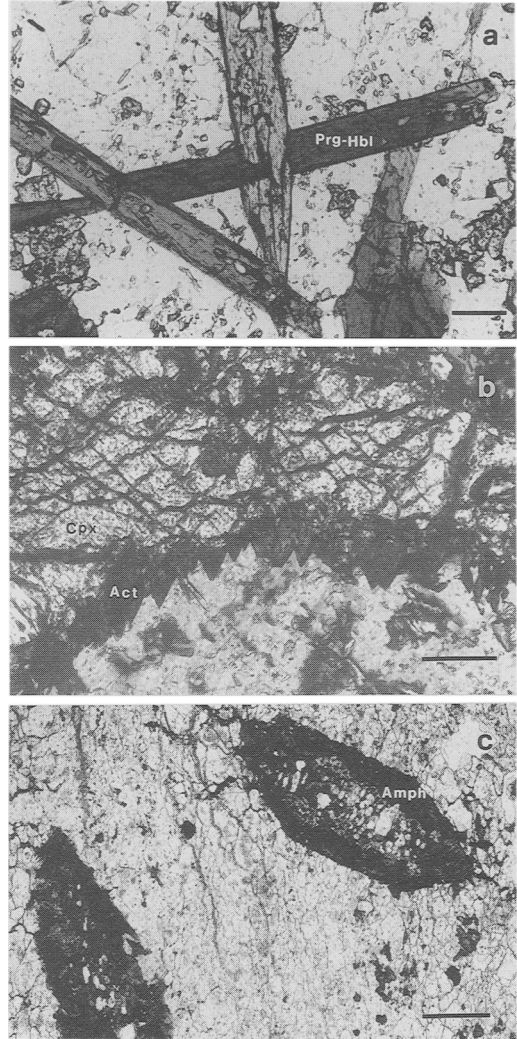


FIG. 4. (a) Pargasitic Hornblendes (Prg-Hbl) randomly orientated and in cross-cutting relation with respect to granular albite and quartz occur in some plagiogranites (scale bar = 100  $\mu$ m); (b) Augitic pyroxene (Cpx) rimmed by an actinolite (Act) fringe in one gabbroic rock (scale bar = 100  $\mu$ m); (c) blue-green amphiboles (Amph) set in a matrix of quartz and albite in one albitite (scale bar = 300  $\mu$ m).

Rb/Sr isotopic data) of gabbroic rocks, plagiogranites and albitites and to verify whether post-magmatic processes seriously modified their primary features. In addition, some inferences are proposed for the genesis of these rocks.

### Analytical methods

Thirty rock samples were analysed by XRF for major oxide and trace element contents. The XR counts were converted to wt.% and ppm using the matrix correction method devised by Franzini *et al.* (1972, 1975) and Leoni and Saitta (1976).

A subset of six samples was chosen for the determination of REE content by ICP-MS. Mineral compositions on selected samples were determined by microprobe analysis using a five-spectrometer ARL SEMQ. Operating conditions were 20 kV accelerating potential, 20 nA beam current with 20 s and 2 s counts for peak and background respectively. The XR counts were converted to wt.% using MAGIC IV program (Colby, 1968).

### Petrography and mineralogy

Apart from primary ferromagnesian phases present in some gabbroic rocks, none of the studied samples shows a primary magmatic mineralogy. In most cases, however, the primary textural features can be recognized.

The occurrence of albite-epidote-actinolite-chlorite-titanite and albite-epidote-blue-green amphibole-biotite assemblages indicates that magmatic lithologies were subjected to conditions of metamorphism ranging from greenschist to epidote-amphibolite facies with later static conditions as illustrated by the textural arrangement of amphiboles (Fig. 4a). The expected increase of An content in plagioclase with metamorphic grade has not been observed.

For the albite-epidote-actinolite-chlorite mineral assemblage the temperatures of metamorphism can be estimated to range from 350–475°C at total fluid pressure of 2 kbar and  $f_{O_2}$  values defined by the QFM buffer (Liou and Ernst, 1979). The albite-epidote-blue-green amphibole-biotite mineral assemblage would be indicative of temperatures higher than 500°C (Liou *et al.*, 1974; Moody *et al.*, 1983).

Gabbroic rocks show a medium to fine heterogeneous grain size and a granular texture. Sometimes they show a cumulate texture. They consist of stubby prisms of actinolite, albite (Ab=99%) (Table 1), clinopyroxene, clinozoisite, quartz and minor quantities of chlorite, titanite and calcite.

Plagioclases show rounded shapes and are replaced by clinozoisite and albite; smaller crystals are euhedral and more commonly twinned. Actinolite is often colourless, but in some samples a pale green pleochroism has been

observed; it also occurs as acicular crystals in cross-cutting relation with all other minerals. Clinopyroxene is subhedral with magmatic embayments and sometimes it is rimmed by a corona made up of amphibole and chlorite (Fig. 4b). Clinopyroxene has an augitic composition with  $Mg/(Mg+Fe) = 0.828$  (Table 1). Calculated Wo, En and Fs components, according to Lindsley (1983), indicate a minimum  $T$  of 1150°C at  $P < 2$  kbar. Microprobe analyses give an actinolitic composition (Leake, 1978) with  $Mg/(Mg+Fe) = 0.857$  for the amphibole and for chlorite a clinocllore composition with  $Mg/(Mg+Fe) = 0.816$ .

Zoned and twinned clinozoisites are present as fine- to medium-grained aggregates occurring in the interstices between actinolites and plagioclases, as well as in veinlets a few mm in length. Intergranular epidote-quartz aggregates are always present.

Plagiogranites show a fine grain size with granular texture and a weak foliation. They essentially consist of quartz, albite, epidote, colourless and blue-green amphiboles; chlorite, biotite and titanite occur as accessory phases.

Plagioclase is present as subhedral and rarely twinned crystals with an invariably albitic composition (up to Ab=99.8%). Occasionally, vermicular quartz-plagioclase intergrowths, interpreted as a primary magmatic textural feature (Coleman and Donato, 1979), have been observed. Amphiboles typically exhibit columnar and acicular shapes and are randomly oriented showing decussate texture (Fig. 4a). Microprobe analyses indicate that colourless amphibole is actinolite with  $Mg/(Mg+Fe) = 0.710$ , while blue-green amphiboles show a small range in composition from ferroan-pargasitic hornblende ( $Mg/(Mg+Fe) = 0.290$ ) to ferro-pargasitic hornblende ( $Mg/(Mg+Fe) = 0.300$ ). Pistacitic epidotes are locally concentrated in bands parallel to foliation. Small biotite flakes show a pale yellow-dark brown pleochroism and are oriented coherently with the weak foliation.

Albitites show a fine grain size and an evident foliation. They are essentially made up of albite and quartz with minor amounts of blue-green amphibole partially replaced by iron oxides and generally displaying corrosion features (Fig. 4c). Accessory phases include monazite, zircon and allanite.

### Geochemistry

The bulk chemical composition of the analysed rocks is given in Tables 2a, 2b and 3; Harker variation diagrams are shown in Fig. 5.

TABLE 1. Selected microprobe analyses of gabbroic rocks (Pak 24/a\*) and plagiogranites (Pak 203, Pak 176\*) from the Mingora ophiolitic mélange

rock type	Cpx 1		Cpx 2		Cpx 3		Act 1		Act 2		Act 3		Prg-Hbl1		Prg-Hbl2		Chl		Ep		Pl 1		Pl 2		Pl 3				
	GB	GB	GB	GB	GB	GB	GB	GB	PG	PG	PG	PG	PG	PG	PG	PG	GB	GB	GB	GB	PG	PG	PG	PG	PG	PG	PG		
wt. %																													
SiO <sub>2</sub>	52.68	52.58	52.47	52.41	56.62	54.51	52.75	40.68	40.46	29.62	36.96	67.21	68.51	68.11	52.68	52.58	52.47	52.41	56.62	54.51	52.75	40.68	40.46	29.62	36.96	67.21	68.51	68.11	
TiO <sub>2</sub>	0.50	0.42	0.26	0.42	-	-	-	0.39	0.34	-	0.06	-	-	-	0.50	0.42	0.26	0.42	-	-	-	0.39	0.34	-	0.06	-	-	-	
Al <sub>2</sub> O <sub>3</sub>	2.63	2.25	2.31	2.67	1.36	0.93	2.90	14.12	13.90	21.73	25.37	20.03	19.36	19.80	2.63	2.25	2.31	2.67	1.36	0.93	2.90	14.12	13.90	21.73	25.37	20.03	19.36	19.80	
FeO	6.42	6.46	6.33	6.61	6.18	11.84	12.34	23.48	22.90	10.27	10.29	-	0.02	-	6.42	6.46	6.33	6.61	6.18	11.84	12.34	23.48	22.90	10.27	10.29	-	0.02	-	
MnO	-	-	0.22	-	-	0.13	0.18	0.25	0.23	0.26	0.05	-	-	-	-	-	0.22	-	-	0.13	0.18	0.25	0.23	0.26	0.05	-	-	-	
MgO	17.25	17.34	17.45	17.49	20.75	16.23	15.08	5.39	5.50	25.53	0.13	-	-	-	17.25	17.34	17.45	17.49	20.75	16.23	15.08	5.39	5.50	25.53	0.13	-	-	-	-
CaO	20.00	20.41	20.52	19.64	12.68	11.81	11.72	10.59	10.49	-	23.25	0.23	0.12	0.04	20.00	20.41	20.52	19.64	12.68	11.81	11.72	10.59	10.49	-	23.25	0.23	0.12	0.04	
Na <sub>2</sub> O	-	0.44	0.44	0.56	-	0.08	0.25	1.86	1.89	-	-	11.58	11.88	11.64	-	0.44	0.44	0.56	-	0.08	0.25	1.86	1.89	-	-	11.58	11.88	11.64	
K <sub>2</sub> O	-	-	-	-	0.12	0.02	0.06	0.52	0.48	-	0.01	-	0.05	0.05	-	-	-	-	0.12	0.02	0.06	0.52	0.48	-	0.01	-	0.05	0.05	
Total	99.48	99.90	100.00	99.80	97.71	95.55	95.28	97.28	96.19	87.41	96.12	99.05	99.94	99.64	99.48	99.90	100.00	99.80	97.71	95.55	95.28	97.28	96.19	87.41	96.12	99.05	99.94	99.64	
Formula																													
Si	1.936	1.932	1.928	1.925	7.874	7.955	7.757	6.309	6.333	5.737	6.054	2.966	2.996	2.984	1.936	1.932	1.928	1.925	7.874	7.955	7.757	6.309	6.333	5.737	6.054	2.966	2.996	2.984	
Al <sup>IV</sup>	0.064	0.068	0.072	0.075	0.126	0.045	0.243	1.691	1.667	2.263	1.946	1.042	0.998	1.022	0.064	0.068	0.072	0.075	0.126	0.045	0.243	1.691	1.667	2.263	1.946	1.042	0.998	1.022	
Al <sup>VI</sup>	0.050	0.030	0.028	0.041	0.097	0.115	0.260	0.893	0.900	2.703	2.952	-	-	-	0.050	0.030	0.028	0.041	0.097	0.115	0.260	0.893	0.900	2.703	2.952	-	-	-	
Ti	0.114	0.012	0.007	0.012	-	-	-	0.045	0.040	-	0.007	-	-	-	0.114	0.012	0.007	0.012	-	-	-	0.045	0.040	-	0.007	-	-	-	-
Fe	0.197	0.198	0.194	0.203	0.718	1.445	1.518	3.045	2.997	1.663	1.410	-	0.001	-	0.197	0.198	0.194	0.203	0.718	1.445	1.518	3.045	2.997	1.663	1.410	-	0.001	-	
Mn	-	-	0.007	-	-	0.016	0.022	0.033	0.030	0.043	0.007	-	-	-	-	-	0.007	-	-	0.016	0.022	0.033	0.030	0.043	0.007	-	-	-	
Mg	0.944	0.949	0.956	0.957	4.300	3.530	3.304	1.246	1.283	7.369	0.032	-	-	-	0.944	0.949	0.956	0.957	4.300	3.530	3.304	1.246	1.283	7.369	0.032	-	-	-	-
Ca	0.787	0.830	0.808	0.773	1.889	1.846	1.847	1.760	1.759	-	4.081	0.011	0.006	0.002	0.787	0.830	0.808	0.773	1.889	1.846	1.847	1.760	1.759	-	4.081	0.011	0.006	0.002	
Na	-	0.031	0.031	0.040	-	0.022	0.070	0.559	0.573	-	-	0.991	1.007	0.989	-	0.031	0.031	0.040	-	0.022	0.070	0.559	0.573	-	-	0.991	1.007	0.989	
K	-	-	-	-	0.021	0.004	0.011	0.103	0.096	-	0.002	-	0.003	0.003	-	-	-	-	0.021	0.004	0.011	0.103	0.096	-	0.002	-	0.003	0.003	
Sum ox	6	6	6	6	23	23	23	23	23	28	25	8	8	8	6	6	6	6	23	23	23	23	23	28	25	8	8	8	
Sum cat	3.992	4.050	4.031	4.026	15.025	14.978	15.032	15.684	15.678	19.778	16.490	5.009	5.010	5.000	3.992	4.050	4.031	4.026	15.025	14.978	15.032	15.684	15.678	19.778	16.490	5.009	5.010	5.000	
Mg/Mg+Fe	0.827	0.827	0.831	0.825	0.857	0.710	0.685	0.290	0.300	0.816					0.827	0.827	0.831	0.825	0.857	0.710	0.685	0.290	0.300	0.816					
Na/(Ca+Na+K)																													
En	48.970	50.499	51.237	51.576											48.970	50.499	51.237	51.576											
Fs	10.224	6.781	5.461	6.799											10.224	6.781	5.461	6.799											
Wo	40.806	42.720	43.302	41.625											40.806	42.720	43.302	41.625											

GB = gabbroic rock; PG = plagiogranites.

TABLE 2a. Selected chemical analyses of mafic rocks from the Mingora ophiolitic mélange

wt. %	Gabbroic rocks												Pillow lavas	
	Pak 15•	Pak 24/a•	Pak 48•	Pak 49•	Pak 132•	Pak 133•	Pak 134•	Pak 194	Pak 197	Pak 202	Pak 16•	Pak 157•	Pak 158•	
SiO <sub>2</sub>	46.67	50.72	44.10	40.67	48.41	49.72	50.93	51.33	50.11	49.99	56.15	46.71	45.63	
TiO <sub>2</sub>	0.22	0.18	0.12	0.09	0.10	0.15	0.08	0.05	0.06	0.06	0.15	1.81	1.19	
Al <sub>2</sub> O <sub>3</sub>	10.59	14.63	14.50	17.08	14.88	15.71	13.21	14.11	12.91	15.93	13.36	12.13	15.56	
Fe <sub>2</sub> O <sub>3t</sub>	9.45	5.72	5.57	5.87	8.25	8.14	7.60	5.79	7.85	5.83	16.17	13.30	12.13	
MnO	0.14	0.10	0.12	0.12	0.13	0.15	0.13	0.12	0.12	0.10	0.08	0.19	0.21	
MgO	20.46	12.82	16.17	19.00	11.06	10.83	12.55	13.24	12.71	12.85	9.49	8.55	8.04	
CaO	7.97	10.42	15.01	12.28	13.57	10.59	12.16	11.28	13.97	11.59	9.45	11.48	9.43	
Na <sub>2</sub> O	0.23	2.96	0.95	0.65	1.82	2.29	1.76	2.62	0.96	2.27	4.03	2.44	2.99	
K <sub>2</sub> O	0.81	0.03	0.01	0.01	0.01	0.45	0.02	0.02	0.01	0.01	0.13	0.09	0.28	
P <sub>2</sub> O <sub>5</sub>	0.01	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.01	n.d.	n. d.	0.01	0.10	0.08	
L.O.I.	3.45	2.42	3.45	4.22	1.77	1.95	1.55	1.43	1.29	1.36	0.97	3.19	4.47	
ppm														
Ba	514	32	43	39	32	79	26	27	16	21	51	57	61	
Rb	19	2	2	3	2	13	2	3	2	3	5	4	9	
Sr	7	32	22	25	242	100	138	75	303	62	73	130	29	
Y	10	6	6	3	3	5	7	2	2	2	9	47	36	
Zr	13	2	n.d.	1	5	8	10	1	3	1	18	112	70	
Nb	6	4	4	4	3	4	3	4	3	3	5	4	5	
V	189	134	154	108	174	138	136	120	216	122	98	425	314	
Cr	2239	774	313	414	47	32	184	185	195	161	464	171	436	
Ni	669	180	104	118	42	30	73	110	98	58	121	67	123	

TABLE 2b. Selected chemical analyses of felsic rocks from the Mingora ophiolitic mélange

	Plagiogranites			Aplite	Albitites	
	Pak 13•	Pak 176•	Pak 203	Pak 17•	Pak 121•	Pak 121/a•
wt. %						
SiO <sub>2</sub>	73.82	74.60	65.59	80.56	66.84	66.47
TiO <sub>2</sub>	0.24	0.24	0.46	0.08	0.19	0.16
Al <sub>2</sub> O <sub>3</sub>	11.96	10.98	12.77	10.00	17.29	17.17
Fe <sub>2</sub> O <sub>3t</sub>	3.75	4.46	5.08	0.91	3.45	3.25
MnO	0.03	0.02	0.05	0.01	0.01	0.01
MgO	0.70	0.66	4.22	0.55	0.01	0.11
CaO	2.71	3.37	6.09	2.63	0.44	1.11
Na <sub>2</sub> O	5.97	4.56	4.96	4.87	10.47	10.22
K <sub>2</sub> O	0.05	0.12	0.03	0.02	0.14	0.16
P <sub>2</sub> O <sub>5</sub>	0.06	0.07	0.05	0.02	0.04	0.04
L.O.I.	0.69	0.93	0.69	3.45	1.12	1.30
ppm						
Ba	38	65	30	31	45	38
Rb	2	4	3	2	4	6
Sr	73	143	70	32	49	45
Y	26	23	24	22	110	124
Zr	76	73	47	44	593	547
Nb	6	5	9	7	134	138
V	23	15	191	14	14	14
Cr	30	27	56	12	12	16
Ni	6	4	22	7	6	6

Gabbroic rocks show very low TiO<sub>2</sub>-, K<sub>2</sub>O-, P<sub>2</sub>O<sub>5</sub>-, Rb-, Ba-, Y- and Zr-contents, high MgO contents and sometimes high Na<sub>2</sub>O- and Cr-contents. The *REE* in the two analysed samples (Pak 24/a•, Pak 194) show very low contents, close to detection limits (0.1 ppm) and lower than chondrite values at least for *LREE* (Fig. 6).

Chondrite normalized patterns show N-MORB shapes ( $Ce_N/Yb_N = 0.32$  for Pak 24/a• and  $Ce_N/Yb_N = 0.10$  for Pak 194) but with distinctly lower abundance levels and with a positive Eu anomaly. The composition of the gabbroic rocks appears to contrast with that of the pillow lavas showing typical N-MORB *REE* patterns and Y and TiO<sub>2</sub> contents.

TABLE 3. Selected *REE*, Th and U analyses of rock samples from the Mingora ophiolitic mélange

	Gabbroic rocks		Pillow lava	Plagiogranites			Albitite
	Pak 24/a•	Pak 194	Pak 158•	Pak 13•	Pak 176•	Pak 203	Pak 121/a•
ppm							
La	0.2	<0.1	2.7	3.5	2.3	1.7	153.0
Ce	0.5	0.1	7.4	7.2	5.3	4.3	264.0
Nd	0.7	0.1	8.7	5.7	4.5	4.1	137.0
Sm	0.4	0.1	2.7	1.8	1.5	1.5	24.8
Eu	0.30	0.07	1.20	0.47	0.43	0.41	4.17
Gd	0.8	0.1	4.1	2.8	2.3	2.6	17.8
Dy	0.8	0.3	5.2	3.6	3.2	3.6	11.4
Er	0.7	0.2	3.1	2.6	2.3	2.9	4.3
Yb	0.4	0.2	2.9	2.5	2.2	2.8	3.2
Lu	0.08	<0.05	0.46	0.40	0.38	0.44	0.41
Th	<0.1	<0.1	<0.1	0.3	0.4	0.5	20
U	<0.1	<0.1	<0.1	0.2	0.2	0.1	11



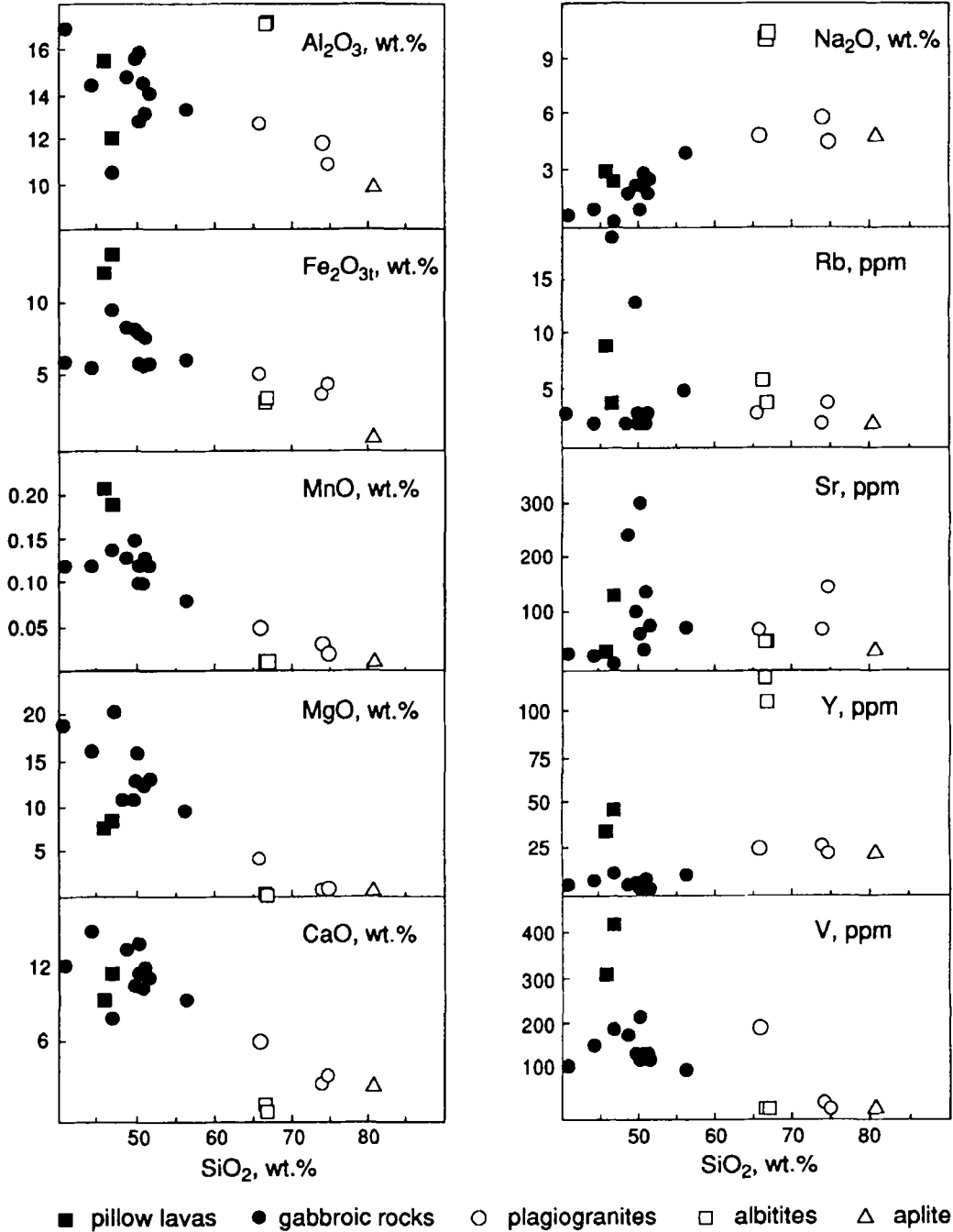


FIG. 5. Selected Harker diagrams for the magmatic rocks of the Mingora ophiolitic mélangé.

Plagiogranites also show low  $TiO_2$ -,  $K_2O$ -,  $P_2O_5$ -, Rb-, Ba- and Zr- and high  $Na_2O$ -contents. In this rock group a sample (Pak 203) has been included which has a bulk chemical

composition intermediate between gabbroic rocks and plagiogranites, having a relatively high  $MgO$ -content (4.22 %) and a lower  $SiO_2$  content (65.59%) with respect to typical plagiogranites.

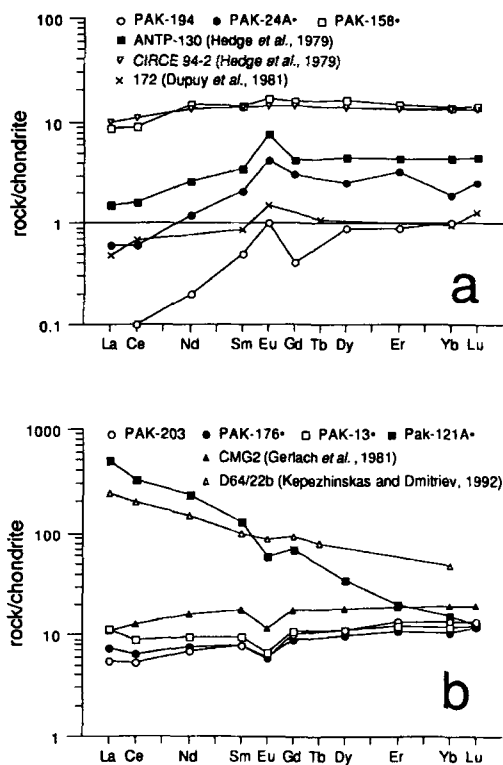


FIG. 6. REE patterns for selected samples from magmatic rocks of the Mingora ophiolitic melange. (a) gabbroic rocks and pillow lava; (b) plagiogranites and albitite. The patterns of one lava (CIRCE 94-2), two gabbros (ANTP 130, 172), one plagiogranite (CMG2) and one granite (D64/22b), from other ophiolitic sequences or oceanic settings, are reported for comparison. Normalizing values after Boynton (1984).

On this basis it should be classified as a tonalite but our terminology conforms to the proposal of Coleman and Peterman (1975) who suggested the term oceanic plagiogranites as a general descriptive definition for trondhjemites, tonalites and albite granites associated with ophiolites.

The REE content is higher than in gabbroic rocks (e.g. from  $5 \times$  chondrite value for LREE to  $14 \times$  for HREE in Pak 203). The REE profiles of the three analysed samples are broadly similar and show an Eu negative anomaly and  $Ce_N/Yb_N$  lower than 1.

Albitites have very peculiar chemical features and for some aspects they appear to be contrasting with gabbroic rocks and plagiogranites. In fact, they exhibit very high contents in Zr, Nb, Y, LREE (Ce  $\approx 300 \times$  chondrite value) and obviously in  $Na_2O$ . On this basis their genesis in

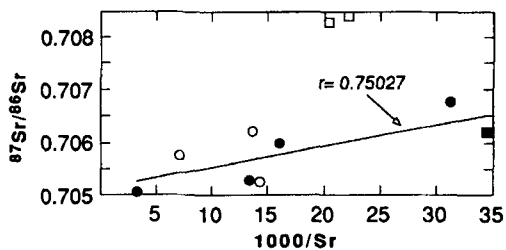


FIG. 7.  $^{87}Sr/^{86}Sr$  vs.  $1000/Sr$  diagram for selected samples of the Mingora ophiolitic melange. The regression line was calculated for all data excluding only albitites. Symbols as in Fig. 5.

the framework of ocean floor magmatism is of problematic interpretation.

Strontium isotope analyses were performed on samples of plagiogranites, gabbroic rocks, albitites and one pillow lava. As shown in Table 4, higher  $^{87}Sr/^{86}Sr$  ratios do not always correspond to higher  $^{87}Rb/^{86}Sr$  ratios.

From the distribution of data points in the  $^{87}Sr/^{86}Sr$  vs  $1000/Sr$  diagram (Fig. 7), it appears that  $^{87}Sr/^{86}Sr$ , excluding albitites, tends to increase as  $1000/Sr$  increases ( $r = 0.750$ ;  $n = 8$ ). Usually this behaviour reflects isotope (and elemental) contamination processes, which are more evident with lower strontium concentration. The contamination process probably derives from interaction with sea water which is a Sr reservoir with an isotopic ratio higher than 0.708. The same contamination process could be responsible also for the observed high  $Na_2O$  concentration levels observed in most rock types.

The high values of  $^{87}Sr/^{86}Sr$  observed in albitites confirm the distinct features of these particular rock types already deduced from trace element concentration levels.

## Discussion

Generally, petrogenetic studies of ophiolitic gabbroic rocks and plagiogranites are complicated by post-magmatic structural, mineralogical and chemical modifications. Actually, ophiolite assemblages commonly bear evidence of hydrothermal alteration, due to intensive sea water circulation in sub-sea-floor environment (Spooner and Fyfe, 1973; Lécuyer *et al.*, 1990), brecciation and later off-axis metamorphism (Liou and Ernst, 1979).

On the whole, the major oxides composition of the studied gabbroic rocks and plagiogranites seems to be weakly affected by metamorphic events, with the major exception of  $Na_2O$  which is relatively high for gabbroic rocks. According to

TABLE 4. Selected whole rock isotopic analyses from the Mingora ophiolitic mélange

Sample	Rb, ppm	Sr, ppm	1000/Sr	<sup>87</sup> Rb/ <sup>86</sup> Sr *	<sup>87</sup> Sr/ <sup>86</sup> Sr ± (2s) **
<i>Gabbroic rocks</i>					
Pak 24/a•	2	32	31.3	0.096	0.70674 ± 3
Pak 194	3	75	13.3	0.116	0.70528 ± 3
Pak 197	2	303	3.3	0.022	0.70505 ± 3
Pak 202	3	62	16.1	0.150	0.70599 ± 4
<i>Pillow lava</i>					
Pak 158•	9	29	34.5	0.865	0.70620 ± 2
<i>Plagiogranites</i>					
Pak 13•	2	73	13.7	0.085	0.70620 ± 2
Pak 176•	4	143	6.99	0.080	0.70574 ± 2
Pak 203	3	70	14.3	0.113	0.70527 ± 3
<i>Albitites</i>					
Pak 121•	4	49	20.4	0.236	0.70830 ± 2
Pak 121/a•	6	45	22.2	0.386	0.70841 ± 2

\* Atomic ratio. \*\* Values normalized to ratio <sup>86</sup>Sr/<sup>88</sup>Sr = 0.1194 and corrected on the basis of Standard NBS 987 SrCO<sub>3</sub>; for this Standard measured isotopic ratio: <sup>87</sup>Sr/<sup>86</sup>Sr = 0.71024 ± 2(2σ). λ<sub>Rb</sub> = 1.42 × 10<sup>-11</sup> a<sup>-1</sup>.

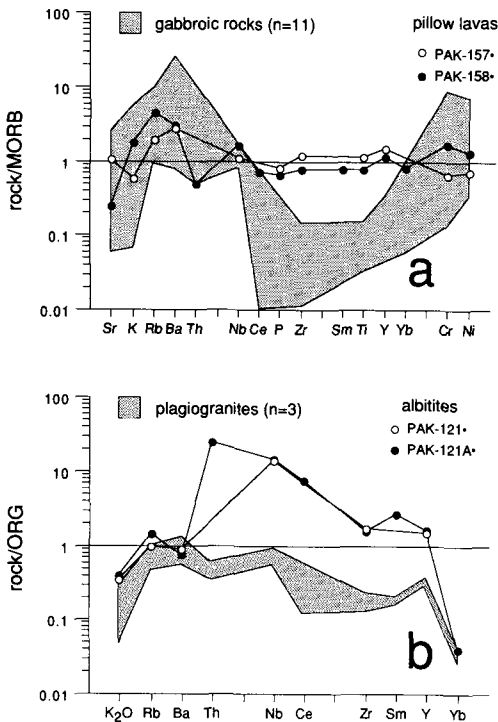


FIG. 8. Spider diagrams for mafic and felsic rocks from the Mingora ophiolitic mélange. Normalizing values after Pearce (1983) and Pearce *et al.* (1984).

Coleman and Donato (1979), the high Na<sub>2</sub>O and low K<sub>2</sub>O in gabbroic rocks and plagiogranites are due to exchange with sea water or to late magmatic vapour-phase transport and removal of K<sub>2</sub>O (Sinton and Byerly, 1980). The availability of Na during metamorphism was probably responsible for the enlargement of the stability field of albite and for the presence of pargasite instead of hornblende observed in the investigated rocks. In Fig. 8, spider diagrams for mafic and felsic rocks show that apart from Sr, K, Rb and Ba which probably underwent mobilization due to metamorphism and/or hydrothermal alteration, the other trace elements may provide reliable information. Pillow lavas confirm a typical N-MORB pattern whereas gabbroic rocks are characterized by a wide spectrum in the elemental abundance levels and by a pronounced depletion in Ce, P, Zr, Sm, Ti and Y. The low concentrations in these elements in part reflect the cumulate character of some samples and in part would suggest the refractory nature of the gabbroic rocks. Plagiogranites display low values in the elemental abundances with respect to ORG (ocean ridge granites, Pearce *et al.*, 1984) with positive anomalies in Nb and Y. The low contents in HFS (high field strength) ions parallels the observed low REE patterns in comparison to typical plagiogranites (Fig. 6b). In contrast, albitites reveal anomalously large amounts of Th, Nb and Ce and to a lesser extent Zr, Sm and Y. Their

TABLE 5. Major element FC models based on least-squares method. At least 80% of  $\Sigma r^2$  derives from  $\text{Na}_2\text{O}$  residual error

FC MODEL	Proportions of the phases in the fractionate			Daughter magma proportion (F)	$\Sigma r^2$
	Pl	Ol	Cpx		
Pak 194→Pak 13•	0.42	0.24	0.34	0.20	0.518
Pak 194→Pak 176•	0.44	0.24	0.32	0.20	0.890
Pak 194→Pak 203	0.42	0.25	0.33	0.28	0.332
Pak 24/a•→Pak 13•	0.46	0.27	0.27	0.22	0.920
Pak 24/a•→Pak 176•	0.47	0.27	0.25	0.22	1.464
Pak 24/a•→Pak 203	0.46	0.28	0.26	0.31	0.596

enrichment in *LREE* is comparable to that of some granitoid xenoliths found in transform-related basalts (Fig. 6b; Kepezhinskas and Dmitriev, 1992). The high Nb contents implicate a WPG (within plate granite) nature if the classification by the tectonic discriminant diagrams of Pearce *et al.* (1984) is adopted.

From the analysis of these features it emerges that gabbroic rocks and to a lesser extent plagiogranites are characterized by very low contents of LIL, HFS and REE elements. This appears to be a primary magmatic feature if HFS ions are immobile during metamorphism (e.g. Floyd and Winchester, 1975). In addition, REE patterns are typical of magmatic rocks associated with ophiolitic complexes (Fig. 6; Coleman and Peterman, 1975; Dupuy *et al.*, 1981). This peculiar chemical feature depends to a certain extent on the cumulate character of the gabbroic rocks. On the other hand, the very low HFS concentration levels maintained also in plagiogranites might suggest an ultimate derivation from refractory melts. According to Duncan and Green (1987), refractory primary liquids, characterized by high MgO and  $\text{SiO}_2$  contents and low  $\text{TiO}_2$  and incompatible elements contents, derive from multistage melting of upper mantle peridotite. The studied intrusive suite should be framed in the context of the low-Ti ophiolites in the classification proposed by Serri (1981).

Common geochemical features shared by gabbroic rocks and plagiogranites, including their Sr isotopic signature, suggest the operation of a differentiation process from mafic to felsic intrusives. Despite numerous studies, there is no general consensus about the nature of the genetic link between gabbroic rocks and plagiogranites. This is confirmed by the contrasting hypotheses proposed for the petrogenesis of plagiogranites: fractional crystallization from a subalkaline tholeiite magma (e.g. Coleman and Peterman,

1975); liquid immiscibility (Dixon and Rutherford, 1979); partial melting of basic rocks under hydrous conditions (e.g. Gerlach *et al.*, 1981; Pedersen and Malpas, 1984); fractional crystallization and filter pressing (Wildberg, 1987). Even though post-magmatic effects have altered the original mineralogy and could have played a role in modifying primary chemical features, the differences in composition from gabbroic rocks to plagiogranites in the Mingora ophiolitic mélange look compatible with a crystal fractionation process. As a preliminary and crude attempt of modelling, mass-balance calculations were performed to reproduce the evolution from gabbroic rocks to plagiogranites. The choice and the composition of the fractionated phases were conditioned both by the results of experimental petrology (Dixon Spulber and Rutherford, 1983; Duncan and Green, 1987) and by the presence in gabbroic rocks of relict magmatic phases such as clinopyroxene. The results of this model are given in Table 5 and indicate ~ 20–31 wt.% of plagiogranitic residual melt with fractionation of olivine, clinopyroxene and plagioclase from a gabbroic parent. An attempt was made to reproduce the REE pattern of the parent magma using the composition of plagiogranites and the results of the mass-balance calculations. The Rayleigh fractionation equation and the solid-liquid partition coefficients in the compilation by Arth (1976) were used. The calculated chondrite normalized profiles are characterized by an enrichment in *HREE* (from 2× chondrite for *LREE* to 5× for *HREE*) with negligible Eu anomaly. If compared to the values observed in the gabbroic rocks, they show higher  $\Sigma REE$ , an absence of a positive Eu spike and larger amounts of *LREE* (Fig. 9). These differences are probably due to a cumulate character of the gabbroic rocks, even though a minor role of metamorphic events in the removal of REE cannot be excluded.

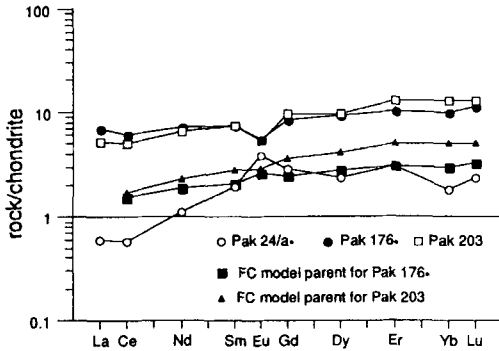


FIG. 9. REE patterns of the parent magma for the plagiogranites (Pak 176, Pak 203) estimated by Rayleigh equation according to a fractional crystallization model. The pattern of one gabbroic rock (Pak 24/a\*) is shown for comparison. The results of major oxides least squares calculations allowed an estimation of the fraction of residual magma (F) and the bulk distribution coefficients introduced in Rayleigh equation. Partition coefficients after Arth (1976).

Therefore, the fractional crystallization process can be a possible mechanism of evolution from gabbroic rocks to plagiogranites in the Mingora ophiolitic mélangé.

More intriguing is the genesis of albitites. As outlined before, they display contrasting chemical features with respect to gabbroic rocks and plagiogranites. In fact, although they have extremely high contents of Th, Nb, Zr, Y and LREE, there are only a few ppm in gabbroic rocks and plagiogranites. In addition they exhibit  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios markedly higher than in plagiogranites, being about 0.708. The enrichment in HFSE and REE could occur in extremely residual liquids affected by conspicuous exchange with sea water and possibly by late magmatic vapour-phase transport. The value of the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio, very close to that of sea water, lends support to this hypothesis. Alternatively, Kepezhinskias and Dmitriev (1992) reported the presence of acidic intrusive rocks showing WPG typology, recovered as xenoliths in transform-related basalts. They interpreted these rocks as fragments of the continental lower crust entrained within transform settings. In this case the genesis of albitites might be in some way linked to within-plate continental magmatic rocks. This second hypothesis is supported by the high values of the concentration levels of elements such as HFSE and LREE, pointing to WPG typology, and by the presence of monazite. More data are needed in order to discriminate these contrasting hypotheses.

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