Petrology of alkali wehrlite sills in the Oman Mountains

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ABSTRACT. Alkaline mafic sills of Jurassic to Cretaceous age in the Oman Mountains have coarse-grained wehrlite centres composed of olivine and zoned diopside–titan-augite with large interstitial poikilitic titanian horn-blendes and titanian barian phlogopites and biotites which appear to have crystallized from a trapped, inter-granular, volatile-rich liquid. The fine-grained chilled margins of the sills are olivine-poor and composed largely of titanaugite, kaersutite, sphene, and interstitial altered plagioclase. The rocks have high contents of incompatible elements (Ti, P, Sr, Ba, Zr, Nb, and others) and steeply inclined, light element enriched, REE patterns. The parent magma is estimated to have been a hydrous alkali picrite with c. 12% MgO from which the wehrlite formed by olivine accumulation. The unusual tectonic setting of the sills, in a Mesozoic continental margin sequence emplaced in an Alpine thrust belt, is noted.

ALKALINE ultramafic sills occur at three localities in the northern Oman Mountains of eastern Arabia (fig. 1). On Jebel Ghawil there are three sills intruded into basaltic lavas and tuffs of the late Triassic Haybi volcanics (Searle et al., 1980) that underlie massive Upper Triassic 'Exotic' lime-stones. The Jebel Ghawil sills give K–Ar ages on separated biotites of 93–4 ± 4Ma (Searle et al., 1980; Lippard and Rex, 1982). On Jebel Ajran there are two sills in a similar tectonic setting, but here they are intruded into lavas that overlie the Exotic limestones (fig. 1). One of the sills gives a K–Ar biotite age of 129 ± 5Ma (Lippard and Rex, 1982). In Wadi Hawasina (fig. 1) an ultramafic sill cuts silicified limestones and cherts belonging to the Upper Triassic Al Ayn formation of the Hawasina series (Glennie et al., 1974; Graham, 1980). This sill gives a mid Jurassic age of 160 ± 6Ma (Lippard and Rex, 1982). In all three areas the sills are conform-able with the country rocks which were folded and thrust during late Cretaceous nappe emplacement. Hornfelsic alteration, hardening, and discoloration of the country rocks can be seen for up to 50 cm from the sill contacts.

The sills range in thickness from 2.5 to 15.0 m and can be divided into three zones: a fine-grained aphanitic outer chilled rind up to 2 cm thick; a fine-to medium-grained equigranular inner chilled zone up to 1 m thick, and a medium- to coarse-grained poikilitic-textured central zone which forms the bulk of the body. The contacts between these zones are transitional and there are no internal chilled contacts.

Petrography

Chilled margins. The outer rinds are aphanitic with small (< 0.3 mm) needles and prisms of clinopyroxene, dark-brown hornblende (kaersu-tite?), and sphene forming a random network in a cloudy, possibly devitrified, matrix. They are clearly the result of rapid quenching against the sill walls. The remainder of the chilled margin has a fine- to medium-grain size (0.1–1.0 mm) increasing towards the centre of the sill, and is composed of small altered olivines, titanaugite, kaersutite, plagioclase, titanomagnetite, apatite, sphene, and biotite (Table I). The texture is 'lamprophyric' with euhedral titanaugite and kaersutite set in a matrix of altered plagioclase. The matrix is largely re-placed by secondary carbonate, small laths of albite and clear patches of analcite.

Sill centres. These are medium- to coarse-grained (0.5–4.0 mm) rocks with a poikilitic texture where partly altered anhedral olivines and subhedral- to euhedral-zoned clinopyroxenes are enclosed in large hornblendes and phlogopitic biotites. Titanomagnetite and apatite are accessories. Small irregular intergranular cavities are infilled with carbonate and analcime. The crystallization sequence is olivine, opaques + apatite, clinopyro-xene, hornblende, then biotite. Occasionally brown hornblende rims the pyroxenes, particularly where they project into the carbonate-filled cavities. Typi-cal modal analyses of the alkali wehrlites are given in Table I.

Mineralogy

Mineral analyses were carried out on the Cam-bridge Instruments Microscan 9 microprobe at the
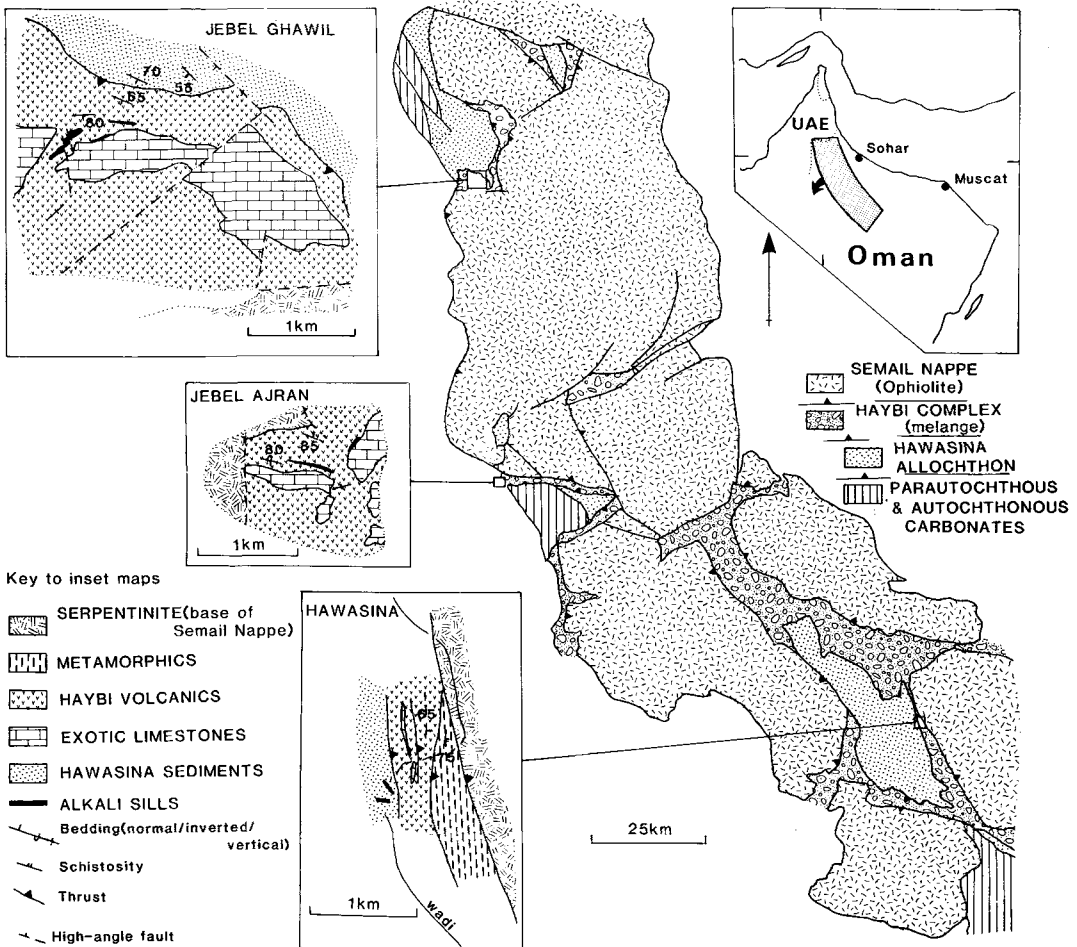
FIG. 1. Geological map of the northern Oman Mountains (simplified from Open University Oman Project map sheets 1–3). Inset maps show detailed geology of the alkali sill occurrences at Jebel Ghawil, Jebel Ajran, and Hawasina.

Open University using mineral and synthetic standards. The results are estimated to be accurate by better than 3 % relative.

Olivines. These constitute up to 35% of the wehrlites as early formed anhedra. They are usually partly serpentinized, leaving fresh cores, and are free from inclusions, showing no significant compositional variation (Fo_{86-85}) either within or between grains (Table II).

Clinopyroxenes. These are also a major constituent of all the rock types, forming up to 45% of the mode. They occur as euhedral to subhedral prisms in the wehrlites where they range up to 3.8 mm long. In contrast to the olivines they are markedly zoned, commonly showing sector and hourglass patterns and colour zoning from colour-

less centres to pale-brown margins. The maximum composition range in a single crystal (Table II) is from a chrome diopside core to titanaugite at the margin (fig. 2). There are systematic core to margin increases in Ti, Al, and Na (fig. 3). The pyroxenes in the chilled margins are colourless to brown titanaugites which fall in the middle of the compositional range of the more strongly zoned crystals in the wehrlites, although they are slightly enriched relative to them in Al and Na (fig. 3). The zoned diopside-titanaugite of these sills is typical of the common clinopyroxenes in alkaline basic rocks (LeBas, 1962; Scott, 1976).

Amphiboles. Dark-brown Ti-rich hornblendes occur as large poikilitic crystals in the wehrlites. They are both edenitic and pargasitic (Leake, 1978)

TABLE I. *Modal analyses of alkali wehrlites*

	1	2
Olivine	35.7	28.3
(% serpentinized)	(80)	(75)
Diopside–augite	28.8	21.1
Phlogopite/biotite	15.1	6.6
Hornblende	13.2	38.0
Opaque Fe–Ti oxides	0.4	2.8
Apatite	0.25	1.6
Sphene		0.5
Altered matrix	5	3
(mainly carbonate)		

1. Poikilitic biotite wehrlite.
2. Hornblende biotite wehrlite.
Modes in vol. % by point counting 1500 points per specimen.

and both compositions can occur in the same rock (Table II and fig. 4), although no zoning from one to the other was found. The pargasite analyses contain up to 0.69 wt. % fluorine. By contrast, the amphiboles in the chilled margins are kaersutites with lower $Mg/(Mg + Fe)$ and higher Ti and K contents than the hornblendes (fig. 5).

Phlogopite and biotite. These occur as small accessory flakes in the chilled margins (too oxidized to be successfully analysed) and large poikilitic plates in the coarse-grained wehrlites where they are generally fresh except for opaque oxidized
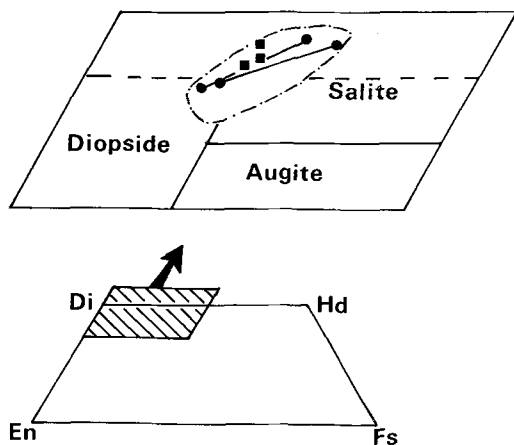

FIG. 2. Clinopyroxene compositions plotted in the pyroxene quadrilateral. Dot-dash line outlines field of diopside–titanaugite compositions from the coarse-grained wehrlites; tie-lines connect core-margin pairs of individual crystals; squares are titanaugites from the chilled margins.
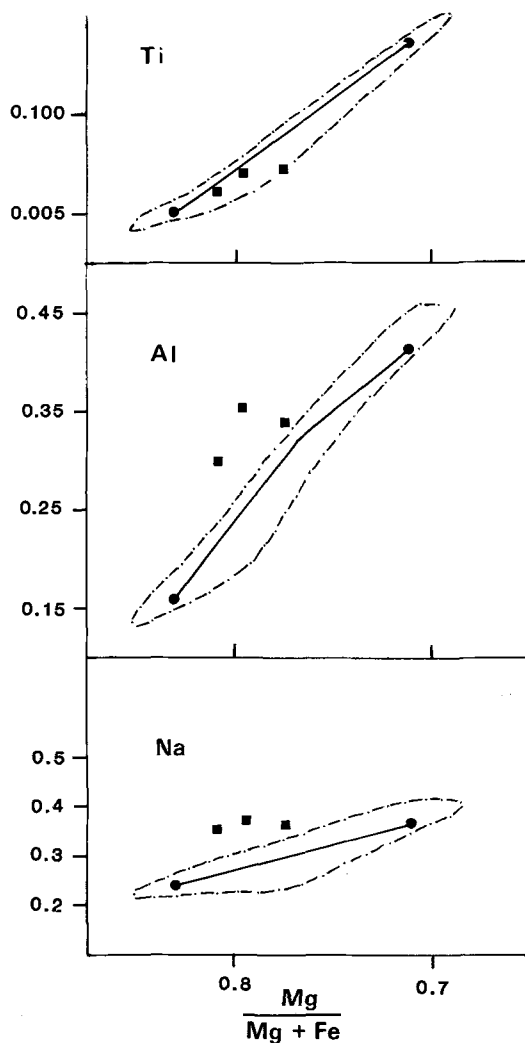

FIG. 3. Ti, Al, and Na versus $Mg/(Mg + Fe)$ plots for clinopyroxenes (symbols as in fig. 2).

margins. The compositions show a wide range from phlogopite to biotite and are generally Ti- and Ba-rich (Table II), although no zoning was detected in individual crystals. They are typical of the high-temperature micas found in alkaline ultramafic and mafic rocks (Wendlandt, 1977).

Geochemistry

Rock analyses by X-ray flourescence techniques were carried out at the Open University and Nottingham University; rare earth elements and Th, Ta, Hf, Sc, Co by instrumental neutron activa-

Table II Representative Mineral Analyses

(a) Olivines and Clinopyroxenes

	1.		2.			3.
	c —— r		c —— i —— r			
SiO$_2$	40.70	40.14	49.79	45.45	41.49	47.30
TiO$_2$			1.79	3.10	5.08	2.21
Al$_2$O$_3$			3.58	7.10	9.84	6.70
FeO	13.53	13.63	5.37	6.48	8.36	5.52
MnO	0.19	0.23	0.11	0.06	0.11	0.08
MgO	46.56	45.91	14.50	12.52	10.55	13.22
CaO	0.23	0.53	23.90	23.75	23.19	23.38
Na$_2$O			0.34	0.41	0.54	0.48
K$_2$O						
Cr$_2$O$_3$	0.02	0.02	0.43	0.28		0.14
NiO	0.26	0.17				
Total	101.49	100.63	99.81	99.15	99.16	99.03
Si	1.000	0.997	1.854	1.719	1.594	1.776
Ti			0.050	0.088	0.147	0.062
Al			0.157	0.317	0.445	0.296
Fe	0.278	0.283	0.167	0.205	0.268	0.173
Mn	0.004	0.005	0.003	0.002	0.003	0.002
Mg	1.706	1.700	0.805	0.706	0.604	0.740
Ca	0.006	0.014	0.954	0.963	0.955	0.940
Na			0.024	0.030	0.040	0.035
Total	2.999	3.002	4.024	4.042	4.056	4.029

1. Olivine, poikilitic wehrlite (OM1827)
   c, core (Fo$_{86.0}$); r, rim (Fo$_{85.7}$)

2. Zoned diopside - titansalite, poikilitic wehrlite (OM1827)
   c, core (Ca$_{49.5}$Mg$_{41.7}$Fe$_{8.8}$); i, inner margin (Ca$_{51.3}$Mg$_{37.6}$Fe$_{11}$)
   r, outer rim (Ca$_{52.2}$Mg$_{33}$Fe$_{14.8}$).

3. Titanaugite, equigranular chilled margin (OM4627)
   (Ca$_{50.7}$Mg$_{39.9}$Fe$_{9.4}$)

(b) Amphiboles and micas

	1.	2.	3.	4.	5.
SiO$_2$	47.32	43.38	35.70	34.08	36.86
TiO$_2$	1.60	3.06	6.16	4.79	6.38
Al$_2$O$_3$	6.83	10.29	16.64	17.31	15.96
FeO	11.53	12.27	15.14	12.40	9.19
MnO	0.25	0.26	0.26	0.17	0.06
MgO	15.71	13.39	11.87	16.45	18.26
CaO	10.33	10.99	9.61	0.01	0.01
Na$_2$O	3.50	4.15	1.83	0.75	0.97
K$_2$O	0.38	0.54	1.09	8.00	7.50
BaO	0.01	0.08	0.29	2.51	0.68
F	0.38				
Cl	0.02				
-F=O	0.16				
Total	98.19	98.44	98.59	96.49	95.89
Si	6.901	6.387	5.348	5.072	5.318
Ti	0.175	0.339	0.694	0.536	0.692
Al	1.174	1.786	2.939	3.037	2.715
Fe	1.406	1.511	1.879	1.543	1.109
Mn	0.031	0.032	0.033	0.021	0.007
Mg	3.414	2.938	2.650	3.648	3.926
Ca	1.614	1.734	1.542	0.001	0.001
Na	0.990	1.185	0.531	0.216	0.271
K	0.071	0.101	0.208	1.519	1.380
Ba	0.001	0.005	0.017	0.146	0.038
F	0.175				
Cl	0.005				
Total	15.957	16.022	15.859	15.559	15.457

1. Edenite, hornblende biotite wehrlite (OM1834)
2. Titanian pargasite,(OM1834).
3. Kaersutite, chilled margin (OM4627).
4. Phlogopitic biotite,chilled margin (OM4627).
5. Titanian phlogopite, hornblende biotite wehrlite (OM1834).

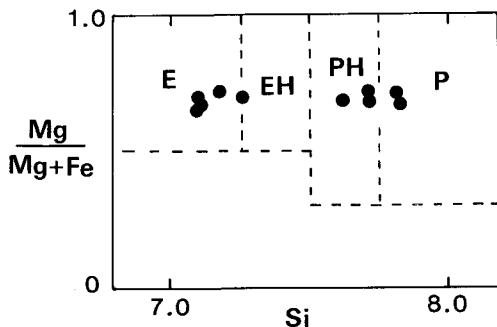Olivine analyses recalculated to 4 O, pyroxenes to 6 O, amphiboles to 23 O and micas to 24 O.

FIG. 4. Hornblende analyses from sample OM1834 plotted on Mg/(Mg+Fe) versus Si diagram of Leake (1978). (E—edenite; EH—edenitic hornblende; PH—pargasitic hornblende; P—pargasite.)

tion analysis at the Open University using the AC(OURS) calibration and the international standard JB-1 as a monitor. Neutron irradiations were made at the University of London Reactor Centre.

The *REE* analytical accuracy is estimated to be 5 % or better (Potts *et al.*, 1981).

The wehrlites have high MgO, Ni, and Cr contents (Table III) appropriate to rocks with 30–35 % modal olivine but this is coupled with relatively high abundances of the so-called incompatible elements (e.g. Ti, P, Ba, Sr, Zr, Nb) which are normally concentrated in the liquid fraction during crystallization or partial melting processes and usually found in low concentrations in ultramafic rocks. Compare, for example, the composition of a cumulate wehrlite, composed of olivine (Fo$_{90-85}$) and diopsidic augite, from the Oman ophiolite (Table III), in which the incompatible elements are about twenty times less abundant than in the wehrlite sills. The incompatible elements are largely concentrated in the interstitial hornblendes and biotites, which contain up to 7 wt. % TiO$_2$ and 3 wt. % BaO (Table II). The rare earth elements are abundant (ΣREE, 432 ppm) and the rocks are strongly light-*REE* enriched with La/Yb up to 122, as illustrated by the steeply inclined chondrite-normalized plots (fig. 6). It is established that kaersutitic hornblendes in alkaline mafic rocks contain ΣREE up to 100 ppm and are enriched in the light elements with La/Yb ratios of 10–50 (Kesson and Price, 1972).

The compositions of the inner and outer parts and the chilled margins of two of the sills are compared with the wehrlite centres in Table IV. The chills are more altered, with higher losses on ignition and CaO, resulting from the carbonate alteration of the matrix. The higher Ti and P contents are expected from the high modal contents of sphene and apatite in these rocks. As well as these elements, the chills are enriched in Sr, Zr, Nb, Y, V, and the *REE* compared with the wehrlites, usually by a factor of 1.5 to 2.0. On the other hand, they
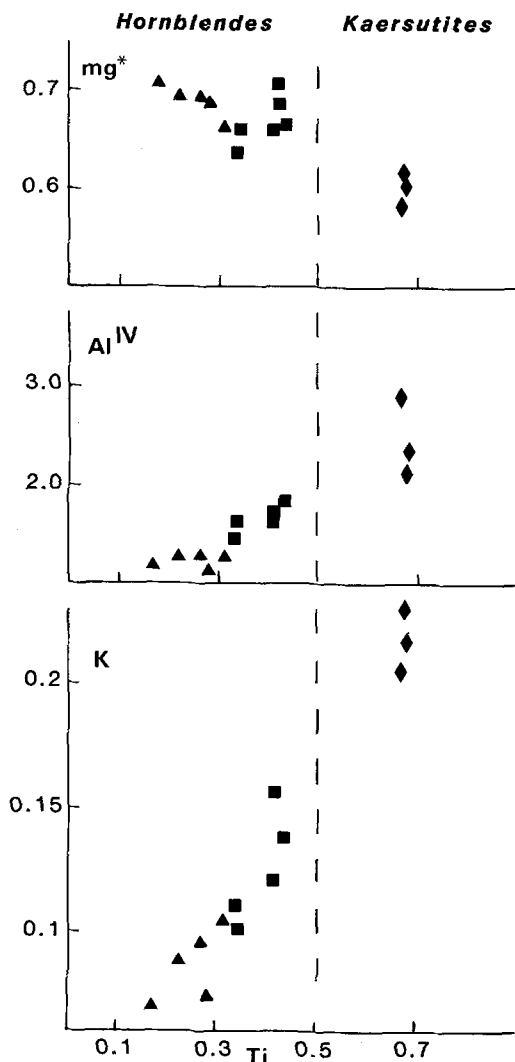
Hornblendes   Kaersutites

TABLE III. *Rock analyses; coarse-grained wehrlites*

	1	2	3	4
SiO_2	38.66	38.25	38.60	48.29
TiO_2	1.80	1.81	1.90	0.17
Al_2O_3	7.10	6.89	6.89	5.13
Fe_2O_3	4.65 ⎫	12.69*	12.90*	7.22*
FeO	7.76 ⎭			
MnO	0.19	0.18	0.20	0.12
MgO	22.74	21.96	21.77	22.12
CaO	8.39	8.91	9.05	12.68
Na_2O	0.36	0.35	0.13	0.10
K_2O	0.66	0.65	1.19	0.04
P_2O_5	0.47	0.57	0.64	0.02
LOI	6.64	6.07	5.61	3.77
Total	99.41	98.77	99.34	99.66
Ba	694	1167	1560	22
Sr	591	786	1047	49
Rb	24	32	47	—
Zr	137	148	156	7
Nb	82	64	74	3
Y	19	23	25	—
V	152	133	145	—
Ni	696	755	727	645
Cr	631	780	531	2429
K/Rb	228	169	210	—

1. OM4675 Poikilitic wehrlite, *c.* 5% biotite. Jebel Ajran. CIPW norm: or 3.90, ab 3.05, an 15.81, di 17.95, hy 3.86, ol 36.97, mt 6.74, il 3.42, ap 1.11.
2. OM8619 Poikilitic wehrlite, *c.* 15% biotite. Jebel Ajran.
3. OM8621 Poikilitic hornblende biotite wehrlite, Jebel Ghawil. (INAA analysis gives La 126, Ce 216, Nd 74, Sm 10.7, Eu 3.04, Tb 1.0, Yb 1.03, Th 8.87, Ta 3.75, Hf 3.3, Sc 16.2, Co 82 ppm.)
4. Cumulate wehrlite (OM2596), Semail Ophiolite, Oman Mountains.
Major elements in wt. % oxides, * total iron as Fe_2O_3. Trace elements in ppm.

FIG. 5. mg*[Mg/(Mg + Fe)], Al^{iv} and K versus Ti plots for amphiboles. (Triangles—edenites; squares—pargasites; diamonds—kaersutites.)

contain less MgO, Ni, Cr, Co, K, and Rb. The transition metals are concentrated in the olivines and most of this chemical variation can be accounted for by olivine addition to the chilled margin composition to form the wehrlite. A least-squares mixing calculation shows that the extraction of about 38% olivine (Fo$_{86}$) from the wehrlite produces a composition that is similar to the average chill composition (Table V). Only Na_2O gives a poor fit and this element was probably mobile during secondary alteration. The wehrlites

are potassic (K_2O > Na_2O), probably as a result of K being stabilized by the crystallization of phlogopite, whereas the margins are more sodic, although the marked increases in Na_2O towards the outer margins can probably be attributed to secondary albitization of the plagioclase.

The origin of the wehrlites by olivine accumulation is supported by the *REE*/chondite patterns of the wehrlite–chill pairs (fig. 6). Each pair from the same sill has a parallel trend, with the lower concentrations in the wehrlites being the result of the dilution effect of *c.* 35% olivine, which contains effectively zero concentrations of *REE*, in the rock.
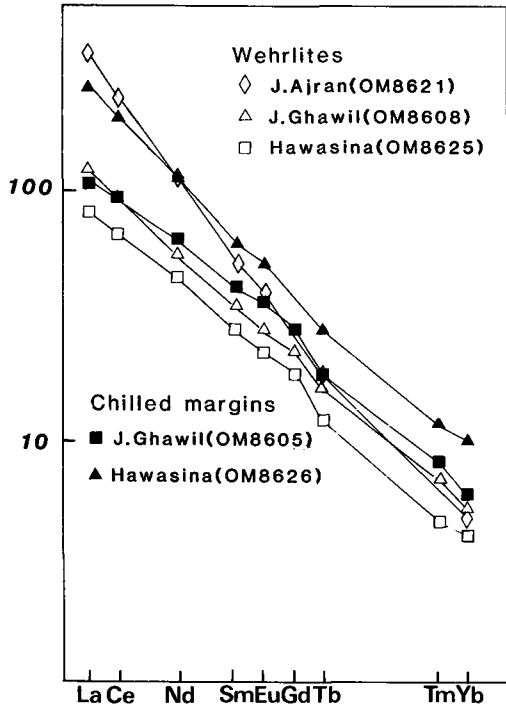
FIG. 6. Rare-earth element chondrite-normalized plots of whole rocks from the Oman sills. Chondrite abundances from Nakamura (1974).

TABLE IV. *Rock analyses; sill traverses*

	Jebel Ghawil sill			Wadi Hawasina sill		
	1	2	3	1	2	3
SiO_2	38.17	35.83	39.26	33.34	40.37	38.95
TiO_2	3.00	3.79	1.80	3.50	3.30	1.96
Al_2O_3	11.67	10.11	6.98	9.70	9.25	5.55
Fe_2O_3*	11.58	12.15	11.55	11.33	11.30	13.02
MnO	0.17	0.18	0.16	0.26	0.16	0.17
CaO	14.00	14.64	10.09	17.77	13.92	6.83
Na_2O	2.85	0.88	1.10	2.57	1.65	0.77
K_2O	0.68	0.76	0.93	nd	0.91	1.01
P_2O_5	0.91	0.98	0.53	0.91	0.66	0.46
LOI	7.87	8.86	4.85	14.87	6.87	6.45
Total	99.63	99.89	99.16	99.77	99.54	98.50
Ba	950	758	752	358	357	645
Sr	824	589	476	599	304	380
Rb	15	8	28	nd	nd	30
Zr	315	332	187	289	246	158
Nb	103	123	55	94	65	45
Y	40	48	25	38	31	17
V	294	317	154	306	261	123
Ni	164	64	825	74	98	918
Cr	415	38	1006	221	242	775
La	75	95	42	—	44	31
Ce	152	182	85	—	93	66
Nd	66	77	37	—	46	32
Sm	12	13	7.2	—	9.6	6.1
Eu	3.6	4.0	2.1	—	3.1	1.9
Gd	—	—	6.4	—	8.9	5.0
Tb	1.4	1.5	0.9	—	1.1	0.7
Tm	0.3	0.4	0.2	—	0.3	0.15
Yb	2.0	2.2	1.15	—	1.4	0.9
Th	10.2	13.0	5.7	—	5.4	4.0
Ta	5.3	6.5	2.85	—	4.0	2.9
Hf	6.7	6.6	4.25	—	6.35	3.7
Sc	19.4	12.8	30.7	—	26.6	17.0
Co	42.7	41.8	75.7	—	43.9	94.5

1. Aphanitic outer chilled margin.
2. Inner chilled margin.
3. Coarse-grained poikilitic centre.
nd not detected.
* Total Fe as Fe_2O_3.

Discussion

The petrography and geochemistry of the wehrlites suggest that they are cumulate rocks formed by the accumulation of about 35 % olivine. There is no evidence for *in situ* crystal settling, so some other concentration mechanism, such as flowage differentiation (Bhattacharji and Smith, 1964), must be involved. Concentration of the olivine grains in the sill centres was followed by the *in situ* crystallization of titanomagnetite, apatite, and diopside-titanaugite and then the late-stage interstitial hornblende and phlogopite-biotite which crystallized from a hydrous residual liquid. The variable compositions of the hornblendes and micas, even in the same rock, point to pockets of residual magma having slightly different composition.

The composition of the magma has been calculated from (i) the average composition of the chilled margins, taking into account the effects of secondary carbonate in the analyses, and (ii) by subtracting 35 % olivine from the average wehrlite composition (Table V). The resulting compositions are picritic with MgO/FeO (mol. %) between 1.8 and 2.0 which is in equilibrium with olivine

(Fo_{86}) at 1270–1310 °C at 1 bar (Roeder and Emslie, 1970).

In Table VI the compositions of the Oman sills are compared with other alkaline magma types and it can be seen that high contents of such elements as Ba, Sr, Zr, and Nb are typical for a whole range of rock types, from alkali basalts to kimberlites. It is difficult to assess the values of such averages for comparative purposes; however, the compositions of the Oman sills are similar to some of the more mafic types of lamprophyres and olivine-rich basanites. The high volatile content of the Oman magmas, as evidenced by the abundance of hydrous phases, is a feature of lamprophyres (Rock, 1977).

Several processes have been advocated to explain why magmas which, while remaining highly magnesian, have high incompatible element contents. The processes fall into two categories: (i) small degrees of partial melting of a garnet lherzolite

TABLE V. *Mixing calculation to obtain the wehrlite by mixing the chill composition with olivine*

	1	2	3	4	5
SiO_2	41.38	40.10	49.79	41.33	41.75
TiO_2	3.65	—	1.79	2.30	1.94
Al_2O_3	11.65	—	3.58	7.31	7.67
FeO	12.68	13.33	5.37	13.14	12.67
MnO	0.22	0.19	0.11	0.21	0.20
MgO	11.41	45.88	14.50	24.74	24.56
CaO	15.40	0.27	23.90	9.70	9.06
Na_2O	1.94	—	0.34	1.23	0.39
K_2O	1.12	—	—	0.71	0.71
Quantity	63.5	+38.5	−0.73	101.5	1.873†

1. Average chill (mean analysis, recalculated to 100%, volatile-free).

2. Olivine (Fo_{86}).

3. Clinopyroxene ($Ca_{49.5}Mg_{41.7}$). Cpx added for completeness but was insignificant in the result obtained.

4. Product generated by the calculation.

5. Average wehrlite (recalculated volatile-free, 'target' composition).

† Sum of squares of residuals.

mantle containing minor phases such as phlogopite, apatite, and zircon rich in incompatible elements. The retention of garnet in the source peridotite is considered the most likely process to account for the light-*REE* enrichment so typical of these rocks, whereas the problem of extracting small amounts of melt (c. 1%) from a dry peridotite (O'Hara, 1965) can be surmounted if the parts of the mantle that are melted have become locally 'metasomatized', i.e. enriched in volatiles and incompatible elements (Lloyd and Bailey, 1975; Bailey, 1980);

(ii) zone-refining or wall-rock alteration processes (Harris, 1957; Green and Ringwood, 1967), whereby the incompatible elements are extracted from the sides of the channels through which the magma ascends. Experimental work on the effects of volatiles on the melting and crystallization behaviour of peridotite, summarized by Wyllie (1977), suggests that melts produced under high CO_2 conditions are generally alkaline and undersaturated. Mysen and Boettcher (1975), in particular, found nepheline-normative melts formed by the partial melting of natural peridotite for vapour compositions with mole fractions of $CO_2 \geqslant 0.5$, and that, with increasing pressure and constant temperature, the FeO/MgO ratio of the melt increases. It is under such conditions that alkaline picritic liquids similar to the Oman magmas could be generated.

Most alkaline mafic and ultramafic magmas are associated with stable intra-plate tectonic settings, usually in continental interiors, although synorogenic mafic alkaline rocks have been described from the Caledonides of Norway (Robins, 1974) and from island arc terrains in the W. Pacific (Nixon et al., 1980). The Oman intrusions were emplaced into a continental margin sequence of Mesozoic turbiditic and pelagic sediments; the Hawasina series of Glennie et al. (1974), and Triassic Haybi volcanic series (Searle et al., 1980) and shallow water marine limestones, the 'Oman Exotics' (Searle and Graham, 1982), that formed during the rifting and subsequent passive margin development of the northern Arabian margin of the Oman Tethys (Graham, 1980). The youngest sills, on Jebel Ghawil, are dated as Cenomanian

TABLE VI. *Comparisons with the trace element contents of the Oman wehrlites*

	Wehrlite	Chilled margins	Lamprophyres (i)	Lamprophyres (ii)	Alkali basalt	Kimberlite
Ba	645–1560	357–950	968	600–2000	528	1000
Sr	380–1047	304–824	839	1460	530	740
Zr	137–197	246–332	168	310	189	250
Nb	45–82	65–123	92	125	69	110
Sc	15–30	13–27			20	15
Y	17–25	31–48			33	22
V	123–179	261–317		45–125	213	120
Ni	598–918	74–164	384	30–110	145	1050
Cr	531–1006	38–415	467		202	1100

(i) Alnoite (Nixon et al., 1980).
(ii) Average monchiquite (Rock, 1977).
Average kimberlite from Wedepohl and Miramatsu (1979).
All values in ppm.

(93–4Ma) which is the same age as the beginning
of late Cretaceous ophiolite obduction and nappe
emplacement towards the continental margin
(Searle and Malpas, 1980). In this respect the age
and tectonic setting of these alkaline magmas in the
Oman mountains is unusual.

REFERENCES

Bailey, D. K. (1980) *Phil. Trans. R. Soc. Lond.* **A297,**
    309–22.
Bhattacharji, S., and Smith, C. H. (1964) *Science,* **140,**
    150–3.
Glennie, K. W., Boeuf, M., Hughes Clark, M. W., Moody-
    Stuart, M., Pilaar, W. F. H., and Reinhardt, B. M. (1974)
    Verh. K. Ned. geol-mijnbouw, Genoot. Part 1 (text),
    1–423.
Graham, G. M. (1980) Ph.D. thesis, Open University
    (unpubl.).
Green, D. H., and Ringwood, A. E. (1967) *Contrib.
    Mineral. Petrol.* **15,** 103–90.
Harris, P. G. (1957) *Geochem. Cosmochem. Acta,* **12,**
    195–208.
Kesson, S. E., and Price, R. C. (1972) *Contrib. Mineral.
    Petrol.* **35,** 119–24.
Leake, B. E. (1978) *Mineral. Mag.* **42,** 533–63.

LeBas, M. J. (1962) *Am. J. Sci.* **260,** 267–88.
Lippard, S. J., and Rex, D. C. (1982) *Geol. Mag.* **119,**
    497–503.
Lloyd, F. E., and Bailey, D. K. (1975) *Phys. Chem. Earth,*
    9, 389–416.
Mysen, B. O., and Boettcher, A. L. (1975) *J. Petrol.* **16,**
    520–48.
Nakamura, N. (1974) *Geochem. Cosmochem. Acta,* **38,**
    757–75.
Nixon, P. H., Mitchell, R. H., and Rogers, N. W. (1980)
    Mineral. Mag. **43,** 587–96.
O'Hara, M. J. (1965) *Scott. J. Geol.* **1,** 19–40.
Potts, P. J., Thorpe, O. W., and Watson, J. S. (1981)
    Chem. Geol. **34,** 331–52.
Robins, B. (1974) *Nor. geol. Tidsskr.* **54,** 247–68.
Rock, N. M. S. (1977) *Earth Sci. Rev.* **13,** 123–69.
Roeder, P. L., and Emslie, R. F. (1970) *Contrib. Mineral.
    Petrol.* **29,** 275–89.
Scott, P. W. (1976) *Mineral. Mag.* **40,** 805–16.
Searle, M. P., and Graham, G. M. (1982) *Geology,* **10,**
    43–9.
——and Malpas, J. (1980) *Trans. R. Soc. Edinburgh
    Earth Sci.* **71,** 247–62.
——Lippard, S. J., Smewing, J. D., and Rex, D. C. (1980)
    J. geol. Soc. Lond. **137,** 589–604.
Wedepohl, K. H., and Muramatsu, Y. (1979) In *Kimber-
    lites, Diatremes and Diamonds: their Geology, Petrology
    and Geochemistry* (F. R. Boyd and H. O. A. Meyer,
    eds.). Am. Geophys. Union, Washington, 300–12.
Wendlandt, R. F. (1977) *Carnegie Inst. Washington Yearb.*
    1976–7, 441–8.
Wyllie, P. J. (1977) *J. geol. Soc. Lond.* **134,** 215–34.