Geol. Bull. Univ. Peshawar, 1986, Vol. 19, pp. 13—19

CALCIUM AMPHIBOLE FROM IGNEOUS ROCKS: MINERALOGICAL PRESSURE INDICATORS

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ABSTRACT

The two methods of PH_2O determination based on Al6 vs. Si (Raase, 1974) and NaM4 vs. Al4 (Brown, 1977) used for amphiboles from metamorphic rocks have been applied to igneous amphiboles (pargasites and their actinolitic overgrowths) from the appinite suite of Scotland, U.K. The method of Raase (1974) is useful for both pargasitic and actinolitic compositions from the appinite suite. The method of Brown (1977) can be applied only to pargasitic compositions. In the actinolitic overgrowths the partitioning of the NaM4 content does not indicate a relation to the existing PH_2O because of crystal chemical limitations.

INTRODUCTION

Ca-amphiboles from igneous rocks have rarely been used as mineralogical pressure indicators, except for calcalkaline plutons (Hollister *et al.,* in prep). The known examples of amphibole which provide such criteria generally belong to metmorphic rocks (Raase, 1974; Brown, 1977). Apart from rare cases, however, reasonable pressure estimates are provided when these criteria are used for Ca-amphibole from igneous rocks in particular of the appinite suite.

Members of the appinite suite occur as intrusions mostly in metasediments of the Dalradian Super group of the Caledonian orogenic belt in various parts of the Highlands and Islands of Scotland and northwestern Ireland (1″ = 10 miles, Geol. Surv. Gt. Britain, Sheet 1). These are subvolcanic pipes and are commonly associated with explosion breccias. Members are pyroxenite, hornblendite, appinite, pyroxene-mica and/or hornblende diorite and granodiorite. These rocks represent a continuous differentiation series and indicate crystallization from a common basaltic parent liquid (at a particular locality). The field relationship, structural control of the pipes and petrography of the suite were described by several workers (Bailey and Maufe, 1916, 1960; Read, 1961; Anderson, 1935, 1937; Nockolds, 1941; Bowes and Wright, 1961, 1967; Bowes, 1962; Bowes, *et al.,* 1963; Platten, 1966; McArthur, 1971) whereas petrogenesis based on mineral and rock chemistry is described by Hamidullah (1983). Detailed information about this latter work, together with analytical techniques and chemical data will be published later (Hamidullah and Bowes, in prep.).

Rhythmic overgrowths (alternating green and colourless bands) of actinolite (in some cases of magnesio-hornblende and actinolitic hornblende compositions) on idiomorphic pargasite crystals occur in appinites from the pipes of Kentallen-Ardsheal peninsula, Ballachulish district. Both pargasite and actinolitic overgrowths are considred to be the product of igneous crystallization (see Bowes *et al.,* 1964; Hamidullah, 1983).

PH_2O DETERMINATION

For PH_2O determination analyses of pargasite crystals and their overgrowths (Table 1) were plotted on the Al6 vs. Si plot of Raase (1974; Fig. 1) and the NaM4 vs. Al4 plot of Brown (1977; Fig. 2). Both these criteria are

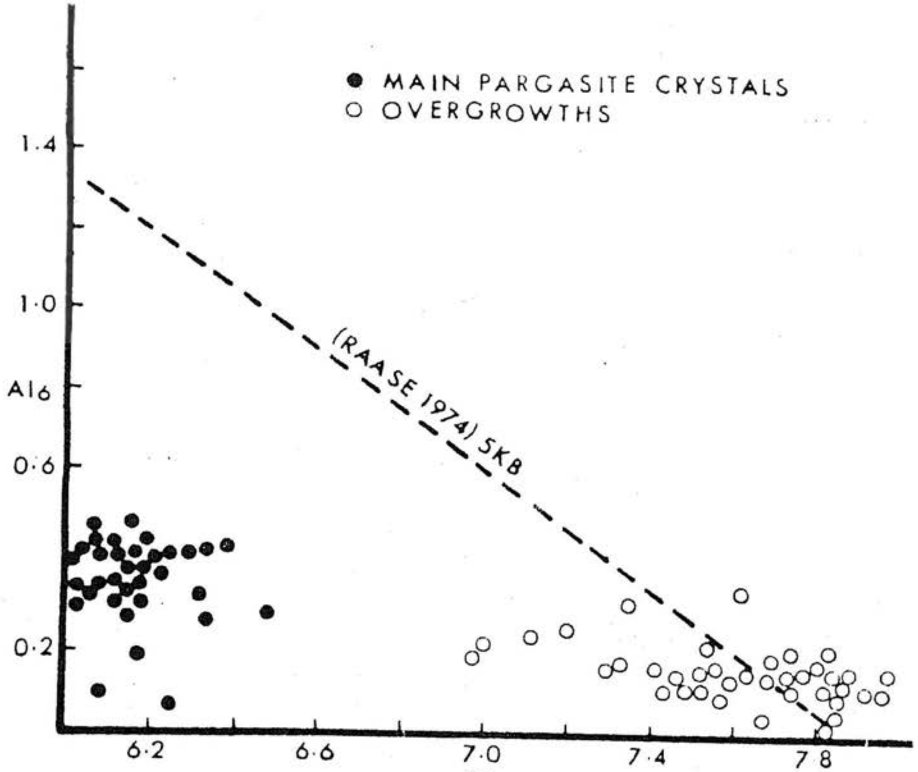

Fig. 1. Tentative pressure estimates on the basis of Al6 *vs.* Si plot of Raase (1974), for amphiboles from the appinite suite of Ballachulish district, Scotland.

TABLE 1. MEAN AND STANDARD DEVIATIONS OF AMPHIBOLE ANALYSES.

	1		2		3	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
SiO_2	41.23	0.86	53.22	1.85	47.99	1.23
TiO_2	1.91	0.47	0.19	0.22	0.11	0.02
Al_2O_3	12.63	0.84	3.14	1.32	7.03	0.10
FeO*	12.27	1.58	12.27	3.77	13.32	1.14
MnO	0.12	0.11	0.26	0.19	0.19	0.14
MgO	13.79	1.05	15.95	2.46	14.74	0.76
CaO	11.88	0.35	12.50	0.50	11.36	0.21
Na_2O	2.20	0.31	0.65	0.49	1.87	0.02
K_2O	1.41	0.28	0.23	0.18	0.75	0.10
Total	97.44		98.41		97.36	
			Formulae on the basis of 23 oxygens			
Si	6.14	0.10	7.62	0.19	6.82	0.27
Ti	0.22	0.05	0.02	0.02	0.11	0.02
Al	2.21	0.14	0.53	0.23	1.55	0.50
Fe	1.53	0.20	1.48	0.49	1.62	0.16
Mn	0.01	0.01	0.03	0.02	0.02	0.02
Mg	3.06	0.22	3.45	0.66	3.19	0.11
Ca	1.90	0.06	1.92	0.06	1.82	0.02
Na	0.63	0.09	0.18	0.13	0.53	0.01
K	0.27	0.05	0.04	0.02	0.04	0.02
Al_4	1.85	0.11	0.38	0.19	1.01	0.06
Al_6	0.36	0.09	0.14	0.07	0.20	0.03

1. Main pargasite crystals (33 anals). FeO* = Total iron as FeO.
2. Actinolitic overgrowths (45 anals).
3. Overgrowths of actinolitic-hornblende and Magnesio-hornblende composition (3 anals).

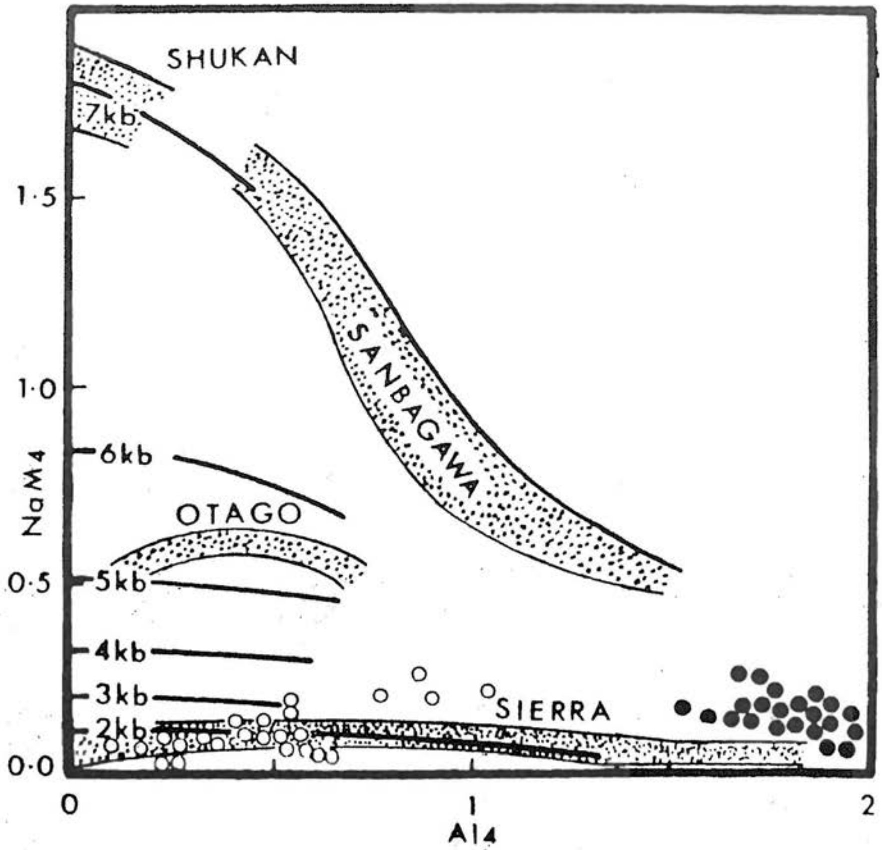

Fig. 2. Tentative pressure estimates on the basis of NaM4 *vs.* Al4 plot of Brown (1977); symbols as in Fig. 1.

based on metamorphic Ca-amphibole. On the former plot, the overgrowths indicate a PH_2O of about 5 kb while pargasites reflect a $PH_2O < 5$ kb (Fig. 1). These estimates are supported by the higher A–site/Al4 ratios of pargasites compared with those of the overgrowths (Fig. 3), which indicate a lower PH_2O during the crystallization of pargasite than of actinolite (see Hietanen, 1974). Also these estimates are consistent with the order of crystallization of various phases in appinites reflected by textural relations, i.e. clinopyroxene, pargasite and overgrowths, respectively, suggesting increasing PH_2O followed by the development of the groundmass feldspar, indicating a drop in PH_2O after the development of the overgrowths (for details see Hamidullah, 1983, p. 196–221, fig. 8.2a).

On the NaM4 vs. Al4 plot (Fig. 2) pargasites show a PH_2O of 2–4 kb which is in accordance with estimates based on the Al6 vs. Si plot of Raase (1974), but the actinolitic overgrowths reflect a PH_2O of 2–3 kb which is con-

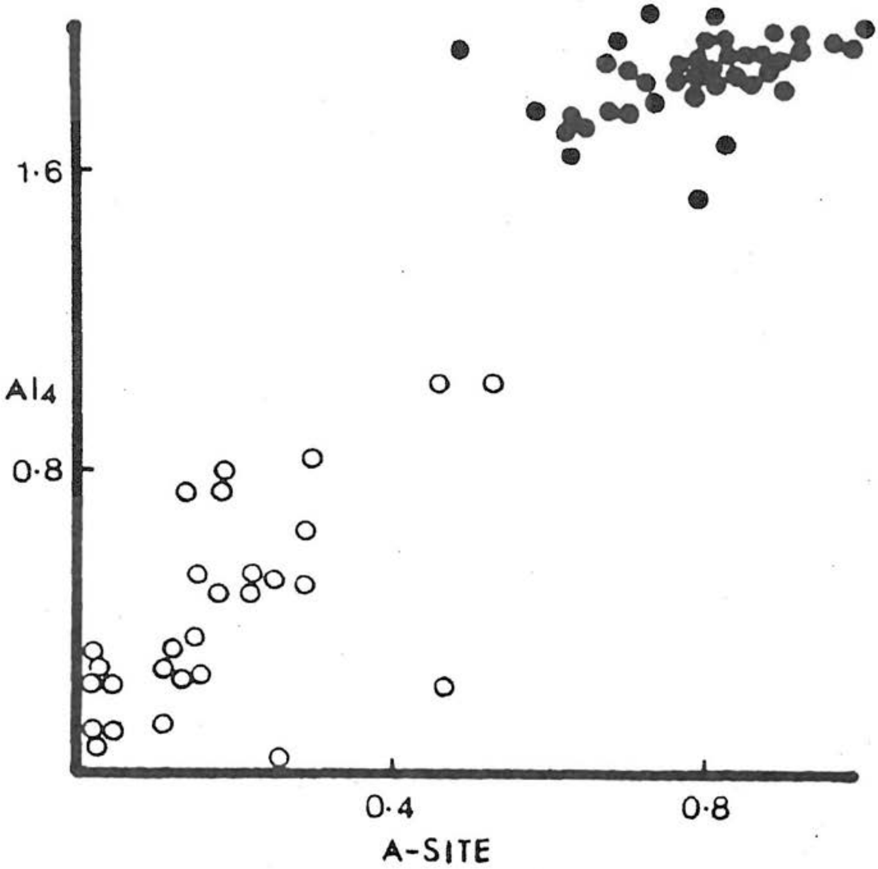

Fig. 3. Al4 *vs.* A-site variation in half unit cell of amphiboles from the Ballachulish appinite suite; symbols as in Fig. 1.

siderably lower than that suggested by the plot of Raase (Fig. 1). There is a clear negative correlation between the NaM4 and Al4 contents of pargasite. Ignoring the four magnesio hornblende compositions (Al4 = 0.7 – 1.1), there is however, no such correlation for the actinolitic overgrowths which have considerably lower NaM4 contents than expected from crystallization of Ca-amphiboles under 5 kb PH_2O (Brown, 1977). This is a manifestation of the crystal chemical limitations on the entry of NaM4 and Al4 into tremolite-actinolite amphiboles (Robinson *et al.,* 1982). The appearance of actinolite on the liquidus requires the removal of Na and Al (the NaM4 + Al4 component in pargasite) by the simultaneous crystallization of albite. The changeover from pargasite crystallization to actinolite-actinolitic hornblende in the appinite suite is effected by the buildup of PH_2O with the resultant reaction :

$$\text{Pargasite} + \text{Silica} = \text{Actinolite} + \text{Albite}$$

Albite is mostly confined to the groundmass in appinites but some albite occurs in the rims of large pargasite crystals, which indicates that it started crystallizing before the formation of the overgrowths.

Low temperature and high pressure favour highly ordered cation distribution in amphibole (Leake, 1971, p. 397). The intensity of green colour in overgrowths possibly corresponds to changes in Fe''' content which increases with increasing oxygen fugasity (cf. Miyashiro, 1973), thus the rhythms in overgrowths indicate variations in gas pressure (Bowes *et al.,* 1964; Hamidullah, 1983, p. 98). It is presumed that crystallization under such variable gas pressure may lead to a less ordered cation distribution in various sites of amphibole even under high PH_2O which would in turn affect the entry of any element into a particular site. Therefore, the entry of Na into the overgrowths may also be influenced by the variable gas pressure in the pipes.

CONCLUSIONS

1. Methods of single amphibole geobarometry for calcic amphiboles developed for metamorphic rocks (Raase, 1974; Brown, 1977) can be applied successfully to igneous rocks, including the appinite suite, provided the varying crystallizing assemblages do not disturb the partitioning of the particular element used for PH_2O determination. The method of Brown (1977) cannot be applied to actinolites because crystal chemical consideration prevent the entry of Na and Al in the same degree as for coexisting hornblendes.

2. In the appinite suite of Scotland, the entry of Na into pargasite occurred under relatively "stable" crystallization conditions and was controlled only by the existing PH_2O. However, in the actinolitic overgrowths this relationship was disturbed by the appearance of albite on the liquidus and the highly variable gas pressure.

Acknowledgements: Professor Brian F. Windley of Leicester University, U.K., Professor M. Qasim Jan and Mr. Munir Humayun of Peshawar University are gratefully acknowledged for critically reading the manuscript and making some valuable suggestions. The financial assistance for this study was provided by the Ministry of Education, Government of Pakistan.

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