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Textural and minerachemical significance of hornblendes from an andesite at Dir, Kohistan arc, N. Pakistan

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ABSTRACT: *Petrography and minerachemical features of a hornblende andesite from Gira Khwar, northeast of Dir proper, are studied to envisage the crystallization mode of hornblende phenocrysts, in the rock. It is determined that the cores of the hornblende phenocrysts are primary igneous. On the other hand the bluish green rims of these phenocrysts and probably the groundmass hornblende are a product of subsolidus re-equilibration and or metamorphic recrytallization. The very tips of the hornblende phenocrysts appear to have recrystallized during shearing and cataclasis at a latter stage.*

INTRODUCTION

Volcanic rocks at Dir and its surrounding (Fig.1) are considered to be an extension of the Utror volcanics of Late Cretaceous age in Upper Swat. These volcanics are part of the Kohistan island arc system. A number of papers have been published on the various aspects of these volcanics in the recent years (Majid & Paracha 1980, Hamidullah et al., 1990; Hamidullah & Onstot, 1992; Suliivan, et al., 1993; Hamidullah, 1993; Shah et al., 1993;). Rock types include basalts, basaltic andesite, andesite, dacite rhyolite, ignimberite, agglomerate and tuffs. These rocks are generally aphyric, but sparsely contain euhedral to subhedral phenocrysts of pyroxene, plagioclase and hornblende (Hamidullah & Onstot, 1992). Regarding the presence of chlorite, epidote and secondary hornblende the prevailence of metamorphism up to green schist facies has been identified by the previous workers (Majid & Paracha, 1979; Shah & Hamidullah, 1994).

Primary amphibole if not rare, is also not a common phase in volcanic rocks. Those volcanic rocks containing amphibole, develop them mostly due to subsolidus changes and metamorphic recrystallization of ferromagnesiam minerals. Nevertheless, limited occurrence of amphibole bearing rocks have been reported from many volcanic suites of the world. When ever reported, however, such amphiboles are subject to debate for their mode of crystallization. In this paper similar amphiboles from a hornblende andesite of Dir volcanics (western part of Dir-Utror volcanics; Fig.1) have been reported. Petrography and mineral chemistry are utilized to establish the mode of crystallization of various amphiboles in this rock.

PETROGRAPHY

Hornblende andesite from Gira Khwar, northeast of Dir proper (Fig.1) is locally carbonated but fresh sections are also common. A fresh sample (LR14) collected from one of the outcrops contains hornblende and plagioclase as phenocrysts, in a groundmass of hornblende, plagioclase, magnetite, quartz and K-feldspar, Minute grains of epidote (?) or sphene (?) may

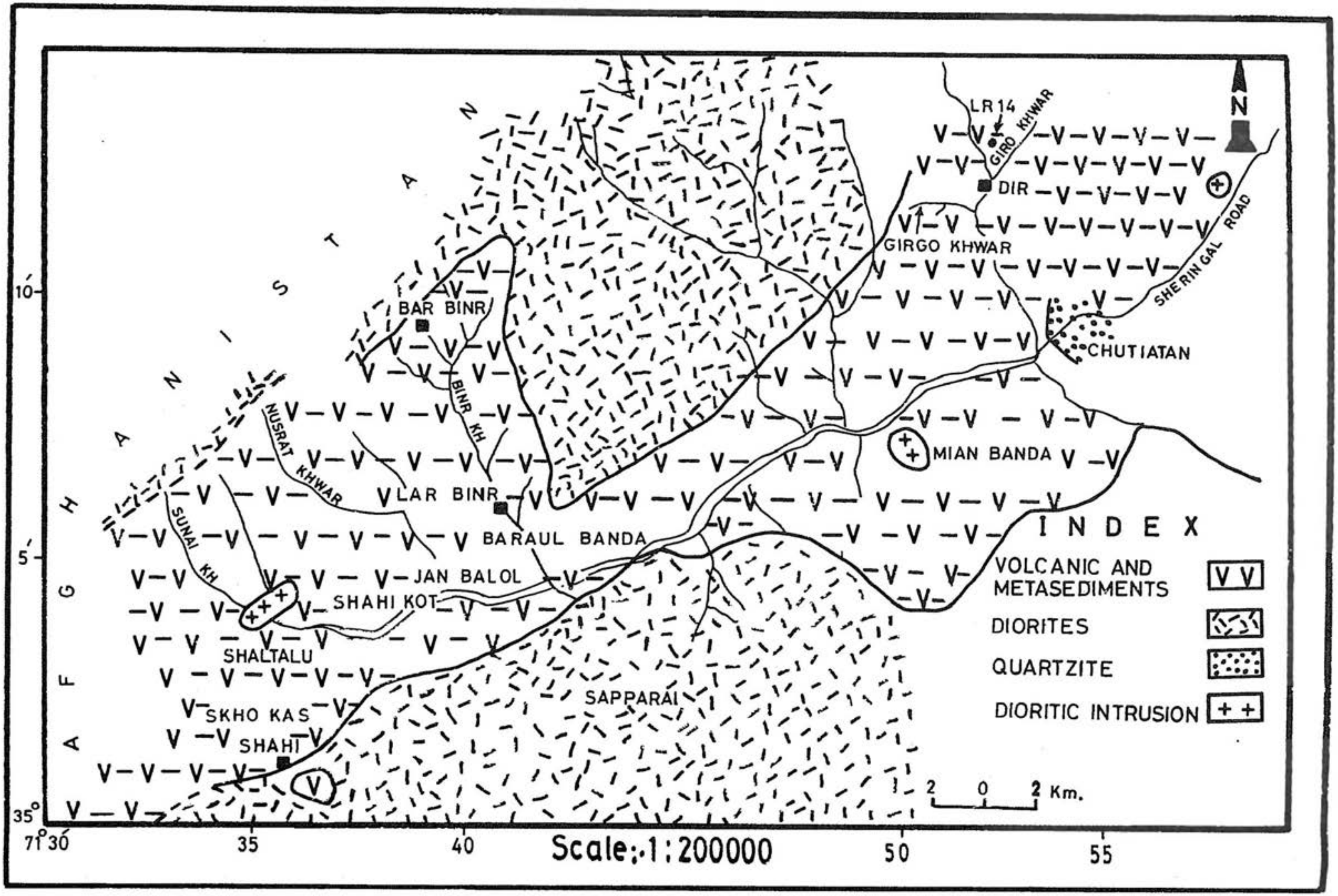

Fig. 1. Geological map of Dir and Baraul valley (modified after Khan, 1979).

occur in association with hornblende in the groundmass.

The hornblende phenocrysts are both stumpy and prismatic in shape and subhedral to anhedral in outlines. Their diameters vary from 1x0.4cm to 0.15x0.15cm. In the plane-polarized light these phenocrysts generally look non-pleochroic dark brown and black. In certain domains however, they turn light brown and even colourless, but still remain non-pleochroic. The phenocrysts are mostly corroded along margins parallel to the long axes. Also these phenocrysts have developed pleochroic green to bluish green amphibole in the form of very thin strips along the corroded margins and as thicker stirps, towards their tips of long axes. The thicker strips are ocassoionally complemented by bluish green amphibole laths at the very tips of long axes (Fig.2).

The plagioclase phenocrysts show a greater variation in shape from perfectly euhedral to completely anhedral, highly corroded and resorbed crystals. Their diameters range between 0.6x0.3cm and 0.4x0.3cm but even smaller grains are not uncommon. These phenocrysts are partially sericitized and have an An% of 94 at cores and 25 at margins. Minute magnetite grains and exalved orthoclase occur in these phenocrysts.

The ground mass contains small acicular and prismatic crystals of hornblende, plagioclase and magnetite with interstitial orthoclase and quartz. The hornblende and plagioclase crystals are generally <0.2x0.05 mm in diameters, indicating a considerable contrast (>1:50) with phenocrysts on the basis of grain size. The hornblende in the groundmass is pleochroic from green to bluish green and is comparable to the margins of the hornblende phenocrysts in this regard. The groundmass generally look sheared, showing the development of a fabric around phenocrysts. In this fabric the growth of the groundmass hornblende crystals seems to have followed the outlines of the partially corroded, slightly rotated and/or truncated phenocrysts. Locally however, patches of phenocrysts + groundmass have escaped

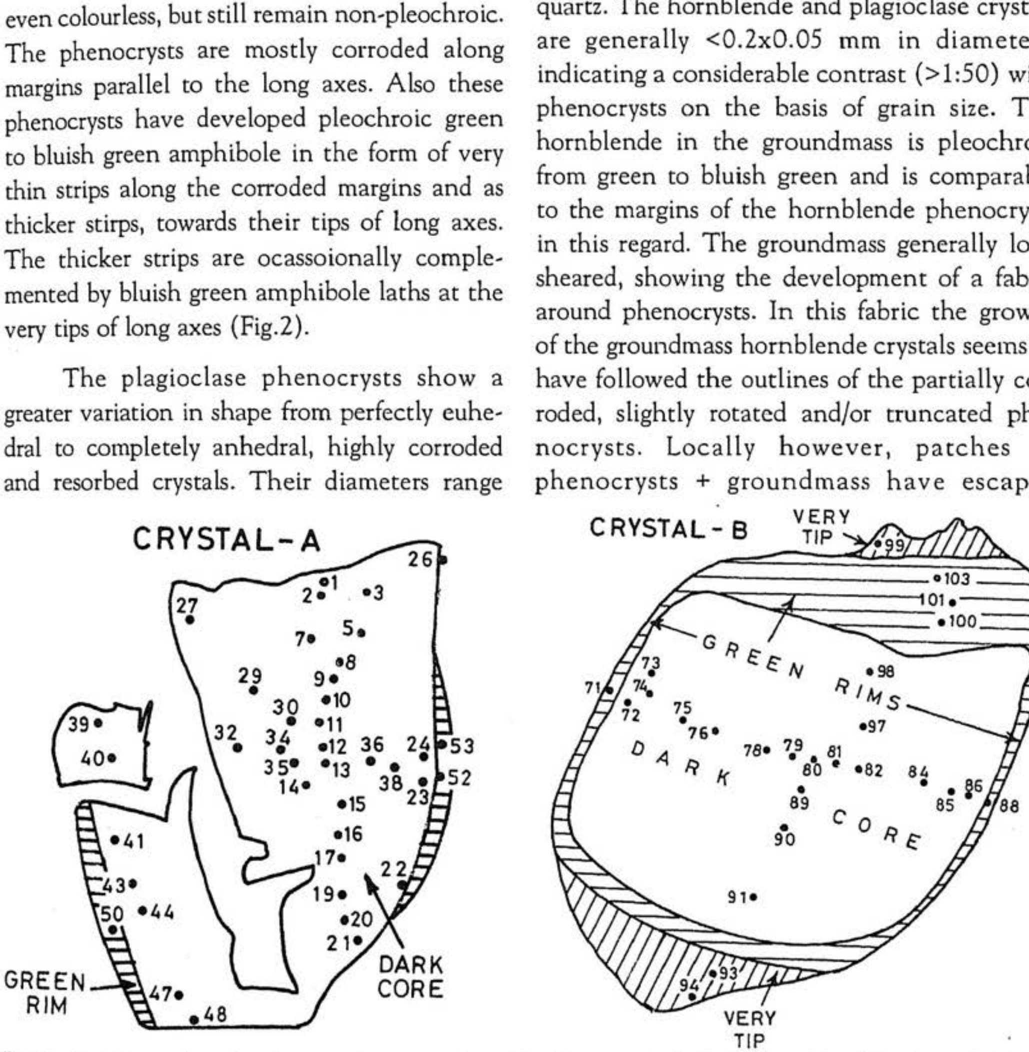

Fig. 2. Positions of analysed spots shown on hornblende crystals A & B from hornblende andesite at Dir.

shearing. In such domains phenocrysts are euhedral and the groundmass lack any fabric.

CHEMISTRY OF AMPHIBOLES

Core to margin spot analyses were carried out on two large hornblende phenocrysts shown in Figure 2. Spots were also analyzed on groundmass hornblende. Analytical procedures have already been published by Hamidullah and Onstot (1992) and also in this volume by Hamidullah (1993a). Formulea were calculated on the basis of 23 oxygens. Ferric-ferrous ratios were fixed using both the 13 cations (excluding K, Na & Ca; minimum) and 15 cations (excluding K & Na; maximum) procedures of Robinson et al. (1982). The mean of both sets of data were taken as the best estimates (see Droop, 1987; Schumacher, 1991). Analyses with totals <95% were discarded leaving behind 65 analyses of the phenocrysts and 2 of the groundmass amphiboles shown in Table 1. These data show a perfect charge balance in Figure 3a. All the analyses have $(Ca+Na)_B$ >1.34 and Na_B <0.67 and are therefore distinguished as calcic amphibole. When classified further on the basis of $(K+Na)_A$, Ti, Fe^{3+} and ^{vi}Al cations according to the IUGS scheme (Leake, 1978), these amphiboles fall in the fields of magnesio-hastingsite, pargasite, farroan-pargasitic hornblende, tschermakite, tschermakitic hornblende and magnesio hornblende. Four analyses which deviate from the general trend, express a compositional gap with the rest of the data and fall in the field of magnesio-hornblende but closer to the field of actinolitic hornblende in Figure 3b, were taken at the bluish green very tips of the hornblende phenocrysts (Figs.3 b, d). In the phenocrysts high tschermakitic and edinitic components correspond to their cores and margins, respectively (see Figs. 2, 3; Table 1). The distribution of data on the basis of $(K + Na)_A$ indicate an edinitic substitution which is typical of igneous hornblende (Helz, 1982). This is also supported by the positive correlation of ^{iv}Al with A-site (Fig. 4a). Other igneous substitutions noticed are Ti-tschermakitic (i.e. $Mg + 2Si = Ti+2^{iv}Al$) and a relatively weaker tschermakitic (i.e. $Si+Mg=^{iv}Al+^{vi}Al$) one, in the phenocrysts (see Figs.4 b, c). On the Ca+Na+K vs Si plot of Leake (1971) most of the data fall well below the "limit line of igneous amphibole" indicating igneous characters. The data from the very tips of phenocrysts however, display a difference by lying relatively closer to the limit line than the rest of data (Fig. 5a). On the other hand, the very tips data, one groundmass analysis, six out of seven of the bluish green rims and a few core analyses of tschermakitic hornblende, magnesio hornblende and ferroan-pargasitic hornblende compositions, taken on the phenocrysts (Fig. 2, 3b, c) fall in the field of metamorphic amphibole on the ^{vi}Al vs ^{iv}Al plot of Fleet and Barnett (1978; Fig. 5a). But on this diagram most of the data from the dark brown and black phenocrysts show igneous characters.

P-T ESTIMATES

Hornblende has been found as a stable phase in andesitic and basaltic andesitic melts at pressure and temperature ranges of 5-18kb and 960-880°C, respectively (see Helz, 1982).Well calibrated geothermometers and geobarometers are not available for igneous calcic amphibole from basaltic and andesitic rocks. The Ti and Al content of hornblendes are so far considered to be varying positively with the temperature and pressure of crystallization, respectively (Helz, 1982). Comparing the trends of basaltic hornblendes from experimental work of Helz (1982) and the maximum Ti contents of a tschermakitic composition from the data under present investigation (0.294; Table 1 analysis HB76), it is suggested that hornblende in the

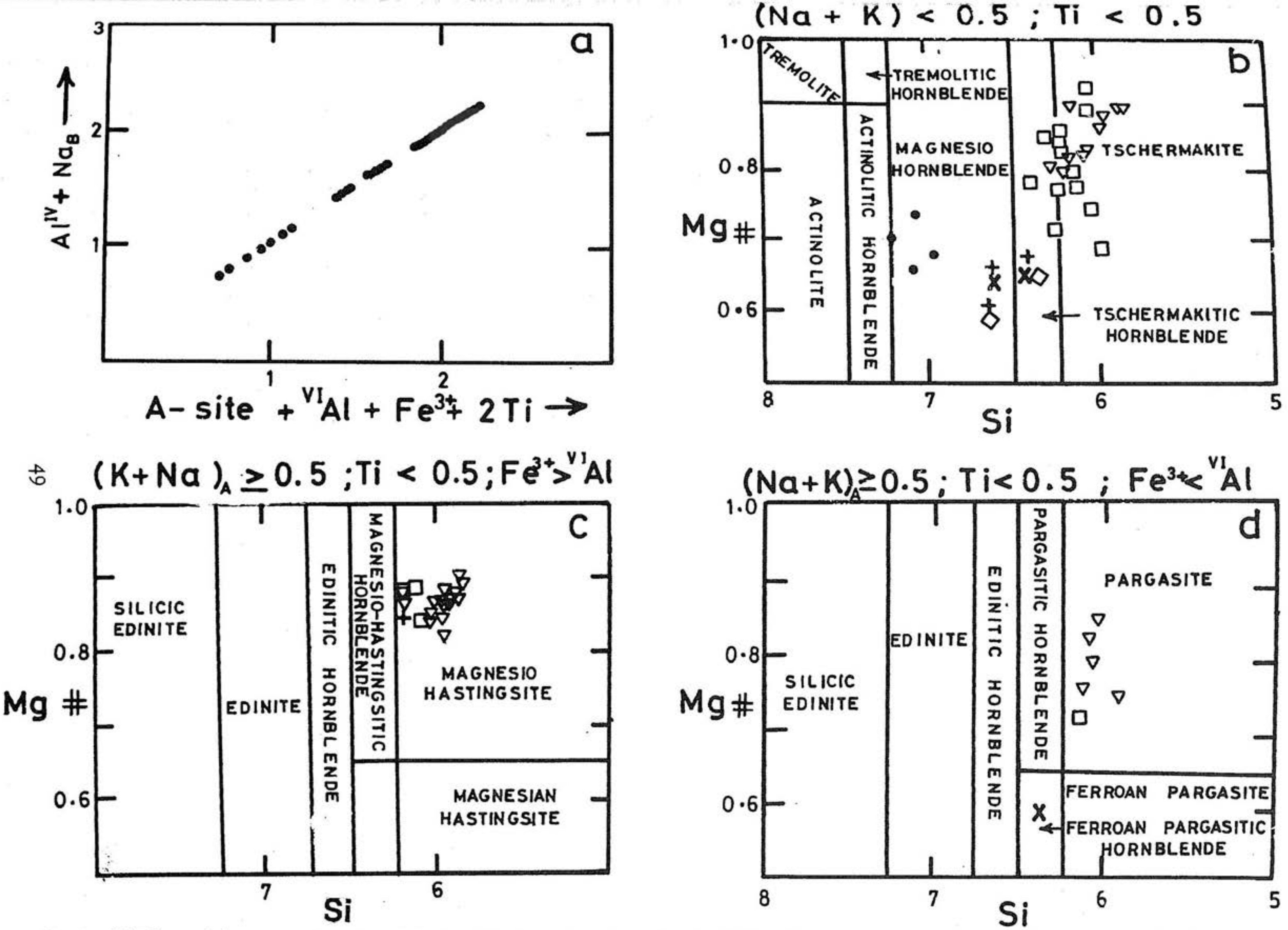

Fig. 3 (a) Charge balance equation plot of the hornblende analyses from Dir. (b-d) Honrblende compositions from Dir shown on the classification diagrams of Leake (1978). Symbols: Cystal A:∇ = dark core, + = green rim,• = very tip; Crystal B:□= dark core, x= green rim; ◊ = groundmass.

TABLE 1. AMPHIBOLE COMPOSITIONS FROM HORNBLENDE ANDESITE AT DIR. S. NOS REFER TO SPOTS ANALYSED ON CRYSTALS SHOWN IN FIGURE 2.

S. nos->	HB1	HB2	HB3	HB5	HB7	HB8	HB9	HB10	HB11	HB12	HB13	HB14	HB15
SiO_2	41.72	40.31	41.79	40.79	41.16	41.38	40.96	40.71	41.14	41.36	40.79	41.10	40.93
TiO_2	01.69	02.02	01.82	01.53	01.84	01.82	01.52	01.65	01.56	01.49	01.55	01.57	01.82
Al_2O_3	14.87	14.87	14.83	15.09	14.84	14.77	14.56	14.62	14.75	15.42	13.98	14.52	14.27
Fe_2O_3	01.22	05.89	02.56	03.78	02.89	03.22	05.00	05.89	04.67	02.44	03.22	05.78	02.33
FeO	08.03	05.14	08.11	06.46	07.45	06.64	05.74	05.48	06.10	07.68	06.45	05.08	07.37
MnO	00.00	00.00	00.00	00.00	00.22	00.27	00.00	00.00	00.00	00.00	00.39	00.43	00.00
MgO	14.42	14.59	14.00	14.48	14.92	14.93	14.98	15.15	15.43	14.86	14.80	14.36	14.46
CaO	12.12	11.95	11.54	11.73	11.56	12.19	12.04	11.90	12.04	11.23	11.65	12.10	11.61
Na_2O	02.47	01.92	01.93	02.22	02.73	02.74	02.50	02.51	02.86	02.60	02.43	01.71	02.39
K_2O	00.22	00.11	00.00	00.10	00.11	00.00	00.00	00.00	00.09	00.00	00.32	00.23	00.00
Cr_2O_3	00.09	00.11	00.03	00.08	00.10	00.10	00.09	00.08	00.08	00.09	00.08	00.21	00.15
Total	96.85	96.91	96.61	96.26	97.82	98.06	97.39	97.99	98.72	97.17	95.66	97.09	95.33
Si	6.069	5.857	6.065	5.952	5.929	5.957	5.929	5.861	5.886	5.956	6.012	5.967	6.034
Ti	0.185	0.221	0.199	0.168	0.199	0.197	0.165	0.179	0.168	0.161	0.172	0.171	0.202
Al	2.550	2.547	2.537	2.596	2.520	2.506	2.484	2.481	2.487	2.617	2.429	2.485	2.480
Fe^{3+}	0.316	0.874	0.610	0.688	0.660	0.541	0.761	0.907	0.752	0.700	0.615	0.819	0.528
Fe^{2+}	0.795	0.395	0.653	0.515	0.551	0.607	0.478	0.390	0.480	0.489	0.538	0.429	0.639
Mn	0.000	0.000	0.000	0.000	0.027	0.033	0.000	0.000	0.000	0.000	0.049	0.053	0.000
Mg	3.126	3.159	3.028	3.149	3.203	3.202	3.231	3.250	3.289	3.189	3.250	3.106	3.176
Ca	1.889	1.860	1.794	1.834	1.784	1.880	1.867	1.835	1.845	1.733	1.840	1.882	1.834
Na	0.697	0.541	0.543	0.628	0.762	0.765	0.702	0.701	0.793	0.726	0.694	0.481	0.683
K	0.041	0.020	0.000	0.019	0.020	0.000	0.000	0.000	0.016	0.000	0.060	0.043	0.000
Cr	0.010	0.013	0.003	0.009	0.011	0.011	0.010	0.009	0.009	0.010	0.009	0.024	0.017
^{iv}Al	1.931	2.143	1.935	2.048	2.071	2.043	2.071	2.139	2.114	2.044	1.988	2.033	1.966
^{vi}Al	0.619	0.404	0.602	0.548	0.449	0.463	0.413	0.341	0.373	0.573	0.441	0.452	0.514
C-Site	5.051	5.065	5.095	5.077	5.100	5.055	5.060	5.077	5.072	5.123	5.073	5.054	5.076
A-Site	0.677	0.487	0.432	0.558	0.667	0.699	0.629	0.613	0.727	0.583	0.667	0.460	0.593
Na_B	0.060	0.075	0.111	0.089	0.116	0.065	0.072	0.088	0.083	0.143	0.087	0.064	0.090

Table 1 continued

S. nos->	HB16	HB17	HB19	HB20	HB21	HB22	HB23	HB26	HB27	HB29	HB30	HB32	HB34
SiO_2	41.73	42.43	41.86	42.84	42.34	43.12	40.47	42.24	40.94	40.29	41.12	40.63	42.34
TiO_2	01.30	01.60	01.63	01.73	01.94	02.49	01.80	01.47	01.86	01.61	02.26	01.96	01.70
Al_2O_3	14.97	11.87	14.84	12.72	12.91	12.29	14.46	11.69	14.70	14.82	14.47	14.73	15.07
Fe_2O_3	04.78	04.56	02.44	03.56	03.22	01.33	07.22	07.11	04.00	03.22	05.22	01.22	02.89
FeO	05.86	06.15	06.85	07.08	08.48	09.84	04.01	06.52	05.62	07.07	05.58	10.00	07.10
MnO	00.33	00.00	00.46	00.00	00.00	00.00	00.00	00.45	00.39	00.00	00.61	00.00	00.63
MgO	15.06	15.61	14.74	15.37	13.77	14.21	14.51	14.39	14.22	14.10	15.34	13.99	14.63
CaO	12.07	11.76	11.85	11.76	11.72	11.24	12.39	11.20	12.04	11.97	12.15	11.98	12.00
Na_2O	02.52	02.09	02.39	02.19	01.63	01.68	01.73	01.40	01.87	02.45	02.52	03.31	02.23
K_2O	00.00	00.12	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.20	00.31	00.30	00.15
Cr_2O_3	00.14	00.10	00.10	00.02	00.00	00.04	00.21	00.02	00.11	00.08	00.13	00.08	00.04
Total	98.76	96.29	97.16	97.27	96.01	96.24	96.80	96.49	95.75	95.81	99.71	98.20	98.78
Si	5.950	6.196	6.043	6.183	6.215	6.289	5.895	6.174	6.003	5.949	5.844	5.918	6.028
Ti	0.139	0.176	0.177	0.188	0.214	0.273	0.197	0.162	0.205	0.179	0.242	0.215	0.182
Al	2.516	2.043	2.525	2.164	2.234	2.113	2.483	2.014	2.541	2.579	2.424	2.529	2.529
Fe^{3+}	0.762	0.762	0.536	0.680	0.612	0.545	0.895	1.170	0.619	0.530	0.801	0.346	0.588
Fe^{2+}	0.450	0.490	0.557	0.561	0.785	0.801	0.385	0.409	0.512	0.701	0.421	1.006	0.567
Mn	0.040	0.000	0.056	0.000	0.000	0.000	0.000	0.056	0.048	0.000	0.073	0.000	0.076
Mg	3.200	3.396	3.171	3.305	3.012	3.088	3.149	3.134	3.107	3.102	3.249	3.037	3.104
Ca	1.844	1.840	1.833	1.818	1.843	1.756	1.934	1.754	1.891	1.894	1.850	1.870	1.830
Na	0.697	0.592	0.669	0.613	0.464	0.475	0.489	0.397	0.532	0.701	0.694	0.935	0.616
K	0.000	0.022	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.038	0.056	0.056	0.027
Cr	0.016	0.012	0.011	0.002	0.000	0.005	0.024	0.002	0.013	0.009	0.015	0.009	0.005
^{iv}Al	2.050	1.804	1.957	1.817	1.785	1.711	2.105	1.826	1.997	2.051	2.156	2.082	1.972
^{vi}Al	0.466	0.239	0.569	0.346	0.449	0.401	0.378	0.187	0.544	0.528	0.269	0.447	0.557
C-Site	5.072	5.074	5.076	5.082	5.072	5.113	5.029	5.120	5.048	5.050	5.069	5.060	5.078
A-Site	0.612	0.528	0.579	0.514	0.380	0.345	0.451	0.270	0.472	0.682	0.670	0.920	0.552
Na_B	0.084	0.086	0.090	0.099	0.084	0.130	0.037	0.126	0.059	0.057	0.081	0.070	0.091

Table 1 continued

S. nos->	HB35	HB36	HB38	HB41	HB43	HB44	HB47	HB48	HB50	HB52	HB53	HB71	HB72
SiO_2	41.13	41.75	41.08	40.81	41.80	41.23	40.93	43.10	43.33	43.56	45.85	43.86	41.68
TiO_2	01.21	01.79	01.71	01.89	01.67	01.67	02.29	01.82	02.27	00.50	00.54	00.42	01.51
Al_2O_3	14.28	14.90	14.22	14.13	14.34	15.24	14.60	13.28	12.65	11.14	10.79	12.48	13.87
Fe_2O_3	01.56	00.89	02.56	03.33	01.78	03.00	04.78	04.45	00.33	07.78	03.56	03.89	01.67
FeO	07.66	09.38	07.69	06.48	07.97	06.73	06.23	08.11	10.63	09.91	13.10	12.25	11.34
MnO	00.00	00.00	00.00	00.41	00.00	00.00	00.19	00.00	00.00	00.34	00.00	00.47	00.00
MgO	13.83	13.82	15.03	15.04	14.60	15.29	14.92	14.11	15.32	11.18	11.87	11.00	12.63
CaO	12.52	11.07	11.46	11.94	11.65	11.85	12.01	11.96	10.68	12.50	11.94	11.89	11.40
Na_2O	02.55	01.94	02.87	02.70	02.14	02.69	02.49	01.60	02.35	00.78	01.08	01.23	02.09
K_2O	00.18	00.19	00.00	00.28	00.43	00.32	00.00	00.00	00.36	00.00	00.00	00.00	00.34
Cr_2O_3	00.27	00.12	00.15	00.10	00.10	00.11	00.07	00.00	00.00	00.00	00.00	00.02	00.04
Total	95.19	95.85	96.77	97.11	96.48	98.13	98.51	98.43	97.92	97.69	98.73	97.51	96.57
Si	6.126	6.098	5.979	5.946	6.090	5.914	5.872	6.175	6.208	6.428	6.636	6.446	6.148
Ti	0.136	0.197	0.187	0.207	0.183	0.180	0.247	0.196	0.245	0.055	0.059	0.046	0.167
Al	2.507	2.565	2.440	2.427	2.463	2.577	2.469	2.243	2.136	1.938	1.841	2.162	2.412
Fe^{3+}	0.174	0.533	0.630	0.590	0.491	0.610	0.760	0.747	0.621	0.901	0.628	0.638	0.503
Fe^{2+}	0.954	0.710	0.586	0.565	0.674	0.521	0.503	0.704	0.688	1.186	1.345	1.297	1.080
Mn	0.000	0.000	0.000	0.051	0.000	0.000	0.023	0.000	0.000	0.042	0.000	0.058	0.000
Mg	3.069	3.008	3.260	3.265	3.170	3.268	3.189	3.012	3.271	2.458	2.560	2.409	2.776
Ca	1.998	1.732	1.787	1.864	1.818	1.821	1.846	1.836	1.639	1.976	1.851	1.872	1.802
Na	0.736	0.549	0.810	0.763	0.604	0.748	0.693	0.444	0.653	0.223	0.303	0.350	0.598
K	0.034	0.035	0.000	0.052	0.080	0.059	0.000	0.000	0.066	0.000	0.000	0.000	0.064
Cr	0.032	0.014	0.017	0.012	0.012	0.012	0.008	0.000	0.000	0.000	0.000	0.002	0.005
^{iv}Al	1.874	1.902	2.021	2.054	1.910	2.086	2.128	1.825	1.792	1.572	1.364	1.554	1.852
^{vi}Al	0.633	0.663	0.419	0.373	0.553	0.491	0.340	0.417	0.345	0.366	0.477	0.608	0.560
C-Site	4.999	5.125	5.098	5.062	5.083	5.082	5.071	5.076	5.170	5.009	5.068	5.059	5.092
A-Site	0.768	0.442	0.696	0.741	0.587	0.710	0.609	0.357	0.528	0.209	0.223	0.282	0.555
Na_B	0.002	0.143	0.114	0.073	0.097	0.097	0.083	0.088	0.191	0.014	0.080	0.069	0.106

Table 1 continued

S. nos->	HB73	HB74	HB75	HB76	HB78	HB79	HB80	HB81	HB82	HB84	HB85	HB86	HB88
SiO_2	40.86	41.74	42.49	42.69	41.97	43.00	41.72	42.82	42.91	42.05	42.42	42.67	42.39
TiO_2	01.68	01.83	01.04	02.69	01.84	01.17	01.91	01.74	00.84	01.43	02.58	01.26	00.44
Al_2O_3	13.90	13.42	13.73	12.03	11.67	11.55	11.44	12.65	12.81	12.78	13.25	14.49	12.19
Fe_2O_3	06.00	06.45	03.22	03.67	07.78	04.33	04.00	03.33	04.56	05.00	02.44	04.67	03.45
FeO	10.49	07.18	07.26	07.98	06.66	07.63	09.07	07.89	06.56	08.11	08.69	09.04	13.28
MnO	00.00	00.00	00.48	00.51	00.30	00.00	00.00	00.38	00.32	00.00	00.00	00.51	00.88
MgO	11.54	14.47	14.11	14.28	14.85	14.68	13.53	15.52	15.38	14.55	14.21	12.72	10.15
CaO	12.16	11.40	11.54	11.62	11.43	11.36	11.56	11.24	11.68	11.52	11.82	11.86	12.01
Na_2O	01.81	01.87	01.76	01.56	01.96	01.73	01.82	02.43	02.13	02.36	01.89	01.55	01.65
K_2O	00.19	00.00	00.00	00.00	00.00	00.00	00.14	00.17	00.38	00.00	00.00	00.00	00.46
Cr_2O_3	00.06	00.05	00.03	00.00	00.03	00.04	00.00	00.05	00.03	00.04	00.01	00.00	00.03
Total	98.69	98.41	95.66	97.03	98.49	95.49	95.19	98.22	97.60	97.84	97.31	98.77	96.93
Si	5.984	5.990	6.220	6.205	6.050	6.324	6.238	6.134	6.188	6.090	6.145	6.123	6.372
Ti	0.185	0.197	0.114	0.294	0.199	0.129	0.215	0.187	0.091	0.156	0.281	0.136	0.050
Al	2.400	2.270	2.369	2.061	1.983	2.002	2.016	2.136	2.178	2.182	2.263	2.451	2.160
Fe^{3+}	0.808	1.094	0.665	0.709	1.220	0.821	0.686	0.804	0.806	0.887	0.531	0.790	0.496
Fe^{2+}	1.138	0.463	0.579	0.662	0.426	0.597	0.898	0.500	0.480	0.640	0.788	0.799	1.563
Mn	0.000	0.000	0.060	0.063	0.037	0.000	0.000	0.046	0.039	0.000	0.000	0.062	0.112
Mg	2.518	3.094	3.078	3.093	3.190	3.217	3.014	3.313	3.305	3.140	3.067	2.720	2.273
Ca	1.908	1.753	1.810	1.809	1.765	1.790	1.852	1.725	1.805	1.787	1.834	1.823	1.934
Na	0.514	0.520	0.499	0.440	0.548	0.493	0.528	0.675	0.596	0.663	0.531	0.431	0.481
K	0.035	0.000	0.000	0.000	0.000	0.000	0.027	0.031	0.070	0.000	0.000	0.000	0.088
Cr	0.007	0.006	0.003	0.000	0.003	0.005	0.000	0.006	0.003	0.005	0.001	0.000	0.004
${}^{iv}Al$	2.016	2.010	1.780	1.795	1.933	1.676	1.762	1.866	1.812	1.910	1.855	1.877	1.628
${}^{vi}Al$	0.384	0.260	0.589	0.266	0.050	0.327	0.254	0.270	0.366	0.272	0.408	0.574	0.532
C-Site	5.041	5.115	5.088	5.087	5.108	5.096	5.067	5.127	5.090	5.099	5.076	5.081	5.030
A-Site	0.499	0.388	0.397	0.336	0.421	0.380	0.473	0.559	0.560	0.549	0.442	0.336	0.533
Na_B	0.051	0.133	0.102	0.103	0.126	0.113	0.081	0.147	0.105	0.114	0.089	0.095	0.036

Table 1 continued

S. nos->	HB89	HB90	HB91	HB93	HB94	HB97	HB98	HB99	HB100	HB101	HB103	HB104	HB107
SiO_2	43.96	43.84	40.70	47.63	47.06	41.53	41.86	48.69	43.88	43.32	46.08	45.20	43.83
TiO_2	01.63	01.76	00.84	00.59	00.74	00.89	01.67	00.43	00.29	01.27	00.70	00.32	00.93
Al_2O_3	11.89	12.58	14.84	07.09	08.48	11.68	11.94	07.19	12.85	13.74	10.85	11.04	10.79
Fe_2O_3	01.11	03.33	06.67	00.11	00.67	10.78	04.00	02.11	03.00	05.00	03.11	00.89	04.00
FeO	09.52	08.51	09.09	13.11	12.76	04.45	10.99	11.21	12.53	07.96	14.12	15.12	13.63
MnO	00.00	00.00	00.55	00.59	00.45	00.56	00.21	00.64	00.41	00.32	00.40	00.49	00.74
MgO	14.59	15.32	10.89	13.03	12.61	14.76	12.03	13.95	11.10	13.43	11.45	10.97	11.15
CaO	11.76	11.41	11.53	12.01	11.69	11.07	11.36	11.86	11.89	12.34	11.76	12.05	11.40
Na_2O	02.06	02.09	00.94	01.18	00.59	01.41	01.58	00.65	01.25	01.51	00.99	01.65	01.37
K_2O	00.00	00.00	00.19	00.22	00.25	00.00	00.00	00.00	00.31	00.00	00.21	00.38	00.36
Cr_2O_3	00.00	00.00	00.01	00.02	00.04	00.10	00.00	00.01	00.03	00.05	00.03	00.03	00.05
Total	96.52	98.84	96.25	95.58	95.34	97.23	95.64	96.74	97.54	98.94	99.70	98.14	98.25
Si	6.405	6.223	6.038	7.102	6.988	6.059	6.259	7.088	6.446	6.197	6.629	6.658	6.453
Ti	0.179	0.188	0.094	0.066	0.083	0.098	0.188	0.047	0.032	0.137	0.076	0.035	0.103
Al	2.042	2.105	2.595	1.246	1.484	2.009	2.104	1.234	2.225	2.317	1.840	1.917	1.873
Fe^{3+}	0.388	0.785	1.016	0.131	0.303	1.444	0.742	0.473	0.540	0.711	0.636	0.258	0.767
Fe^{2+}	0.893	0.581	0.856	1.516	1.356	0.282	1.082	1.122	1.331	0.779	1.400	1.703	1.354
Mn	0.000	0.000	0.069	0.075	0.057	0.069	0.027	0.079	0.051	0.039	0.049	0.061	0.092
Mg	3.168	3.240	2.407	2.895	2.790	3.209	2.680	3.026	2.430	2.863	2.454	2.408	2.446
Ca	1.836	1.735	1.833	1.918	1.860	1.730	1.820	1.850	1.871	1.891	1.812	1.902	1.798
Na	0.582	0.575	0.270	0.341	0.170	0.399	0.458	0.183	0.356	0.419	0.276	0.471	0.391
K	0.000	0.000	0.036	0.042	0.047	0.000	0.000	0.000	0.058	0.000	0.039	0.071	0.068
Cr	0.000	0.000	0.001	0.002	0.005	0.012	0.000	0.001	0.003	0.006	0.003	0.003	0.006
^{iv}Al	1.595	1.777	1.962	0.898	1.012	1.941	1.741	0.912	1.554	1.803	1.371	1.342	1.547
^{vi}Al	0.447	0.328	0.633	0.348	0.472	0.068	0.363	0.321	0.672	0.514	0.469	0.575	0.326
C-Site	5.075	5.122	5.077	5.033	5.065	5.181	5.082	5.070	5.059	5.049	5.086	5.044	5.094
A-Site	0.493	0.433	0.216	0.335	0.142	0.310	0.360	0.103	0.345	0.359	0.213	0.489	0.351
Na_B	0.089	0.142	0.090	0.048	0.075	0.088	0.098	0.081	0.070	0.060	0.101	0.054	0.108

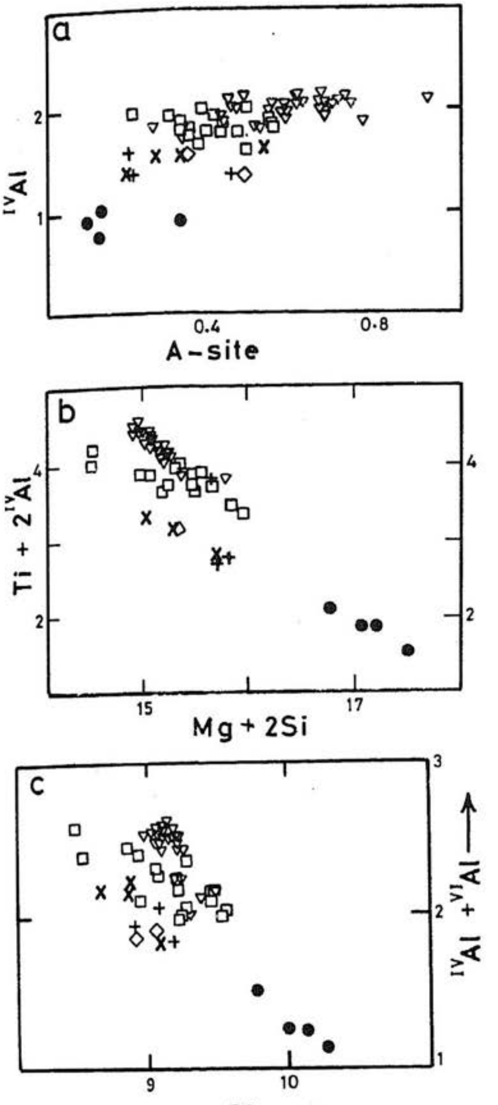

Fig. 4 (a) Edinitic (^{iv}Al vs A-site), (b)Ti-tschermakitic (Ti+2^{iv}Al vs Mg+2Si) and (c) tschermakitic (^{iv}Al+^{vi}Al vs Mg+Si) substituion plots of the hornblende analyses from Dir.

studied rocks appeared on the liquidus in a temperature range of 915-880°C (Fig. 6a). Majority of the data from the brown and dark portions of the phenocrysts have Ti >0.1, indicating crystallization above 700°C. The bluish green margins and the very tips of the phenocrysts as well as analyses from the groundmass hornblende have Ti content <0.1, indicating crystallization below 700°C.

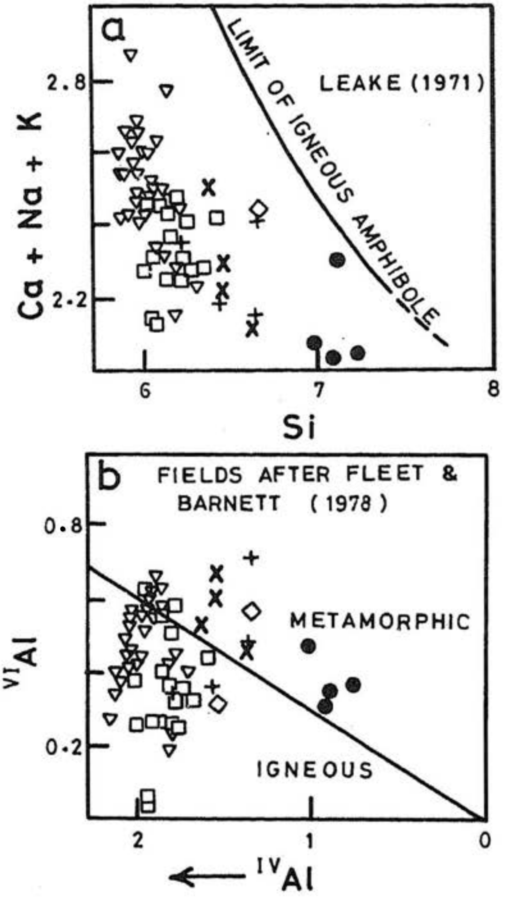

Fig. 5. (a) Ca+Na+K vs Si and (b) ^{iv}Al vs ^{vi}Al discrimination plots of hornblende from Dir.

Hammorson and Zen (1986) and Hollistor et al, (1987) defined geobarometers for igneous hornblendes from calcalkaline plutons which were latter on refined by Johnson and Rutherford (1989). This geoberometer when applied to the current data showed a systematic decrease in pressure (8-4kb) from core to margins of the phenocrysts (except for the very tips) on a P vs Ti plot. The very tips of the phenocrysts, however, reflect pressure condition of 3-<1kb; estimates rather lowerer than those

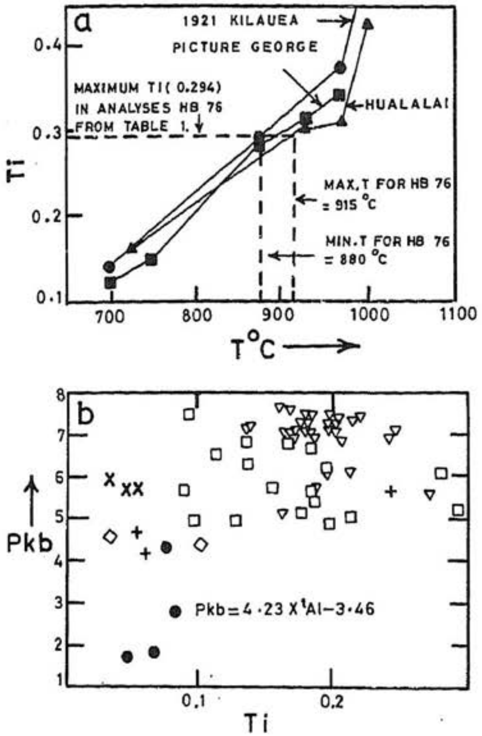

Fig. 6. P-T estimates for Dir hornblende using (a) Ti vs T°C trends of Helz (1982) for temperature determination and (b) the equation (P = 4.23 ^{t}Al-3.46) of Johnsen and Rutherford (1989) for pressure determination.

reflected for the groundmass data (~4.5kb; Fig. 6b). These estimates may be considered tentative because we do not have the evidence for the required coexisting phases (i.e. quartz, plagioclase, biotite, orthoclase, titanite and magnetite) with hornblende in the melt. Nevertheless, the systematic decrease of the estimated pressure from core to margins and the positive correlation between Ti and Al in general indicate decreasing P-T environments during the growth of the phenocrysts. It is also evident from these estimates and other diagrams that the very tips of the hornblende phenocrysts crystallized in a different set of P-T environment than those of the phenocrysts and groundmass.

DISCUSSION

The petrography and mineral chemistry of the hornblende andesite indicate that the cores of hornblende and plagioclase phenocrysts represent primary igneous crystallization of volcanic origin. The existence of both phenocrysts and groundmass, the tremendous contrast between the two on the basis of grain diameters (1:50 in hornblendes), the euhedral to subhedral shapes of the phenocrysts and the numerous signatures of igneous parentage in the chemistry of hornblende phenocrysts, (particularly the dark brown and black cores chemistry) are consistent with such interpretation. This is also in accordance with the age spectrum obtained for these hornblendes phenocrysts on the basis of ^{40}Ar/^{39}Ar techniques; with the cores yielding a plateau date of 70±9.0 Ma and rims reflecting a disturbed spectrum (see Hamidullah & Onstot 1992). On the other hand the development of a fabric in the groundmass following the outlines of the phenocrysts, the corroded, rotated or truncated phenocrysts of both hornblende and plagioclase indicate shearing and cataclasis. This shearing and cataclasis have so far not completely obliterated the major textural features of the rock, i.e. the phenocryst-groundmass relationship. As mentioned earlier various domains of the rock have completely escaped cataclasis and in these domains phenocrysts remain euhedral and the groundmass lack any fabric. Such domains are of vital significance for retaining igneous characteristics. These domains also contain hornblende in the groundmass. Therefore, it appears that the hornblende in the groundmass crystallized before the rock was subjected to cataclasis. This interpretation is in line with the lowerer estimates of pressure obtained on the very tips of the hornblende phenocrysts as compared to those on the groundmass hornblende and the bluish green rims of the phenocrysts. The former probably represent growth during shearing and cataclasis and the latter two at the late stage of igneous crystallization or at subsolidus temperatures or during regional metamorphism (green shist facies mentioned earlier). Most of the bluish green amphibole data fall in the metamorphic field of calcic amphiboles on the ^{vi}Al vs ^{iv}Al plot of Fleet and Barnett (1978, Fig. 5b). However, it is the only chemical evidence showing these hornblendes to be metamoprhic and still more data is needed to confirm such an interpretation. The data obtained for the groundmass hornblende is also meager (only 2 analyses) and therefore, not sufficient for drawing absolute conclusions.

CONCLUSIONS

1. The hornblende and plagioclase phenocrysts in the hornblende andesite from Gira Khwar at Dir represent primary igneous crystallization, at least at their cores; most probably in a temperature range of 915°-700°C and pressure range of 8-4kb.
2. The origin of the bluish green rims of the hornblende phenocrysts and the groundmass hornblende is not clear, but have certainly developed at lowerer P-T than suggested for the cores of hornblende phenocrysts.
3. The bluish green very tips of the hornblende phenocrysts have grown, most probably, during the shearing and cataclasis of the rocks.

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