

Sector zoning of clinopyroxene from a weakly metamorphosed diabase

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Abstract

New data are presented for a sector-zoned clinopyroxene from Loch Lockton, Scotland. Al, Ti, and Ca are enriched, and Mg and Si are depleted, in the (010) and (100) sectors relative to [001]. This pattern of sector zoning differs from that of other reported occurrences of sector-zoned clinopyroxene. No model of sector zoning has yet been given to account for different patterns of sector zoning in one mineral species.

The data also show that sectoral differences in composition in clinopyroxene can survive low-grade metamorphism.

Introduction

Hour-glass or sector zoning is observed in clinopyroxenes from terrestrial and lunar basalts. Recent studies of the chemical inhomogeneities in these pyroxenes based on microprobe analyses include those of Strong (1969), Hargraves *et al.* (1970), Hollister and Hargraves (1970), Bence *et al.* (1970), Hollister and Gancarz (1971), Hollister *et al.* (1971), Wass (1973), Nakamura (1973), and Leung (1974). As the number of descriptions of individual cases has increased, it has become clear that the compositional distinctions of sectors in sector-zoned pyroxenes are not the same for each case. They apparently differ as a result of differences in bulk composition and prior crystallization history as well as in differences in cooling histories. However, the very existence of these differences may enhance the potential usefulness to petrology of the understanding of sector zoning.

We describe results for sector-zoned pyroxenes from the Girvan-Ballantrae Igneous Complex, Scotland. No attempt is made to interpret the data in the context of models of crystal growth and the origin of sector zoning (see Dowty, 1976, for a recent discussion of this subject); however, they are presented because they add a new variation to those already published and therefore are essential to an ultimate understanding of sector zoning. The fact that they occur in an otherwise altered (by low-grade metamorphism) igneous rock serves to illustrate that through an understanding of sector zoning a means of understanding the origin of basaltic rocks in low-grade metamorphic terranes may be provided, be-

cause the chemistry of sector-zoned pyroxenes appears to resist changes due to metamorphism.

Results

The Girvan-Ballantrae Igneous Complex is a poorly exposed, structurally complex Ordovician ophiolite. The major rock types of the complex include serpentized peridotite, gabbro, diabase, pillow basalt, chert, and black shale. These rocks locally show effects of metamorphism to the greenschist and, occasionally, lower amphibolite facies. Further discussion of the geology and tectonics of the area can be found in Harkins (1973).

A diabase from the Loch Lockton area of the complex contains well-developed sector-zoned titaniferous augites. These augites contain up to three weight per cent TiO_2 and occur as 0.25 mm phenocrysts in a groundmass altered by low-grade metamorphism. In addition to pyroxene, major phases in the rock are biotite, chlorite, sericitized plagioclase, titanite, ilmenite, and minor apatite. Crystal faces in the pyroxenes are moderately well developed parallel to the *c* crystallographic axis, but terminal faces are not present. The grains show an anomalous blue birefringence. Prominent sector zoning is apparent under crossed nicols as differences in extinction angle and birefringence and, in plane light, as differences in pleochroism (pale pink to green).

The two crystals discussed below have mutually perpendicular *c* axes as determined by universal stage measurements. Observation of these and sectors in other orientations allows construction of an idealized

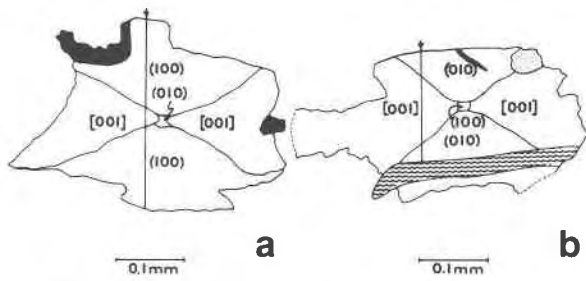


Fig. 1 Sketches of clinopyroxene grains, as viewed in thin section, for which data are reported in Figure 3 and Table 1. The black is ilmenite; the wavy-patterned area is an altered plagioclase crystal; the speckle-patterned area is a titanite crystal. The lines with arrowheads mark the lines of traverses (Fig. 3). The direction is right to left on Fig. 3.

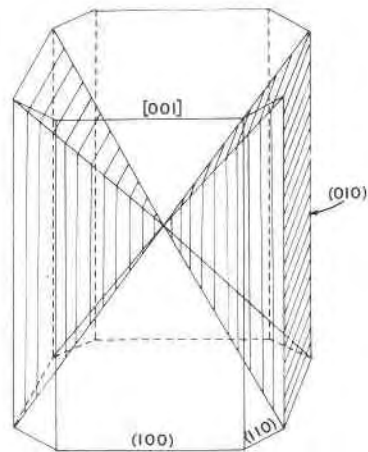


Fig. 2 Sketch of clinopyroxene crystal with forms (010), (110), and (100), showing the relative development of these forms for the study samples. The form(s) for the [001] sector were not identified.

Table 1. Analyses of clinopyroxene sectors

study	1				2			3		4				
	(100)	(111)	(010)	(110)	(100)	(010)	(110)	n.r.	n.r.	(100)	(100)	[001]	(010)	[001]
SiO ₂	46.40	50.25	46.86	45.70	50.7	50.4	50.8	41.7	47.3	47.33	47.33	50.63	46.69	51.62
Al ₂ O ₃	6.43	2.42	5.23	5.86	2.04	2.60	2.48	10.7	6.27	5.91	7.30	2.58	6.36	2.58
Cr ₂ O ₃	n.r.	n.r.	n.r.	0.03	0.06	0.05	0.02	0.02	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.
TiO ₂	1.32	0.75	0.86	1.00	1.20	1.52	1.52	5.40	2.92	2.65	3.16	1.05	2.79	1.12
FeO*	6.48	4.78	6.34	6.38	12.7	10.7	10.6	7.81	7.07	11.55	10.65	10.64	10.23	10.17
MgO	10.07	16.59	13.91	13.46	16.5	14.9	14.8	9.54	12.0	11.47	11.70	16.05	12.19	15.61
MnO	0.06	0.09	0.09	0.12	0.24	0.23	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.
CaO	23.83	23.73	23.70	23.57	15.2	18.7	19.2	22.9	22.4	19.94	19.93	17.46	20.34	18.17
K ₂ O	0.02	0.01	0.01	0.01	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.
Na ₂ O	0.23	0.10	0.21	0.21	0.26	0.31	0.31	0.69	0.52	n.r.	n.r.	n.r.	n.r.	n.r.
Total	98.85	98.71	97.20	96.31	99.0	99.4	99.9	98.0	98.5	98.86	98.13	98.42	98.63	99.29
CATIONS**														
Si	1.758	1.881	1.802	1.778	1.914	1.897	1.902	1.599	1.792	1.806	1.774	1.911	1.780	1.926
Al _{IV}	0.242	0.107	0.198	0.222	0.086	0.103	0.098	0.401	0.208	0.194	.256	0.089	0.220	0.074
Al _{VI}	0.045	0.000	0.039	0.047	0.005	0.012	0.012	0.083	0.069	0.072	.075	0.026	0.066	0.040
Cr	n.r.	n.r.	n.r.	n.r.	0.001	0.002	0.001	0.000	0.001	n.r.	n.r.	n.r.	n.r.	n.r.
Ti	0.038	0.021	0.025	0.029	0.034	0.043	0.043	0.157	0.084	0.076	.091	0.030	0.080	0.032
Fe	0.205	0.150	0.204	0.208	0.401	0.337	0.331	0.251	0.233	0.369	.342	0.336	0.324	0.318
Mg	0.794	0.926	0.797	0.781	0.930	0.834	0.824	0.546	0.678	0.653	.670	0.903	0.693	0.868
Mn	0.002	1.003	0.003	0.004	0.011	0.008	0.007	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.
Ca	0.967	0.952	0.977	0.983	0.616	0.755	0.771	0.938	0.910	0.815	.821	0.706	0.831	0.727
K	0.001	0.000	0.001	0.000	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.
Na	0.017	0.008	0.015	0.016	0.019	0.023	0.022	0.051	0.018	n.r.	n.r.	n.r.	n.r.	n.r.

Study: 1. Hollister and Gancarz (1971) crystal 1
 2. Nakamura (1973)
 3. Wass (1973)

4. This study
 * All Fe as FeO
 ** On the basis of 6 oxygens

n.r. not reported

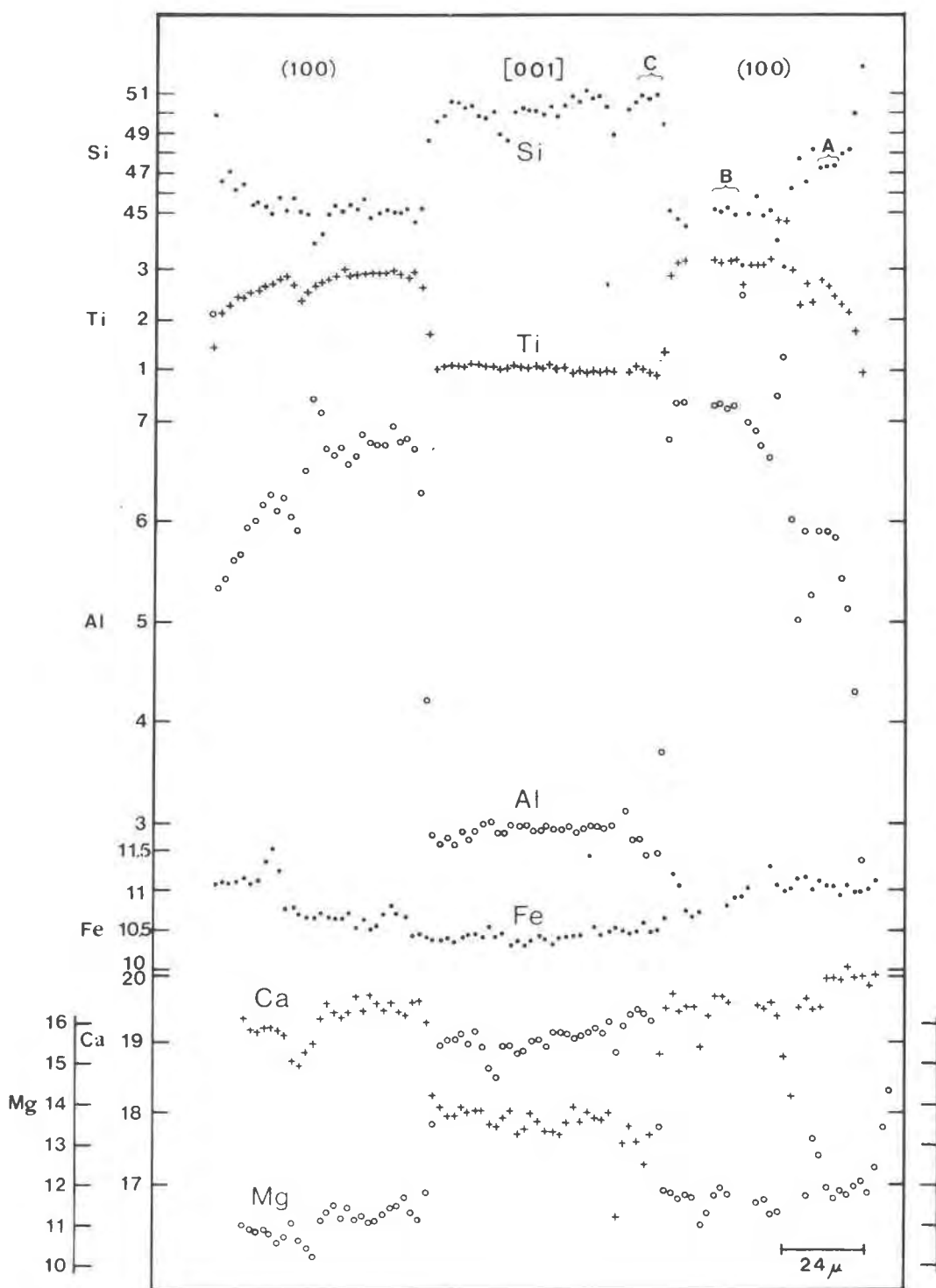


Fig. 3a. Variations of the elements Si, Ti, Al, Fe, Ca, and Mg along traverse (a), Fig. 1. Analysis points reported in Table 1 are identified by letters.

pyroxene morphology for these crystals. This morphology and sketches of the described grains are illustrated in Figures 1 and 2.

Sectors are pyramid-shaped, with apices at the

crystal center and bases forming crystal faces. Where these faces are developed, the sector is named for the face formed by its base. Where no face is developed, the zone symbol, $[hkl]$, is used. When the plane of the

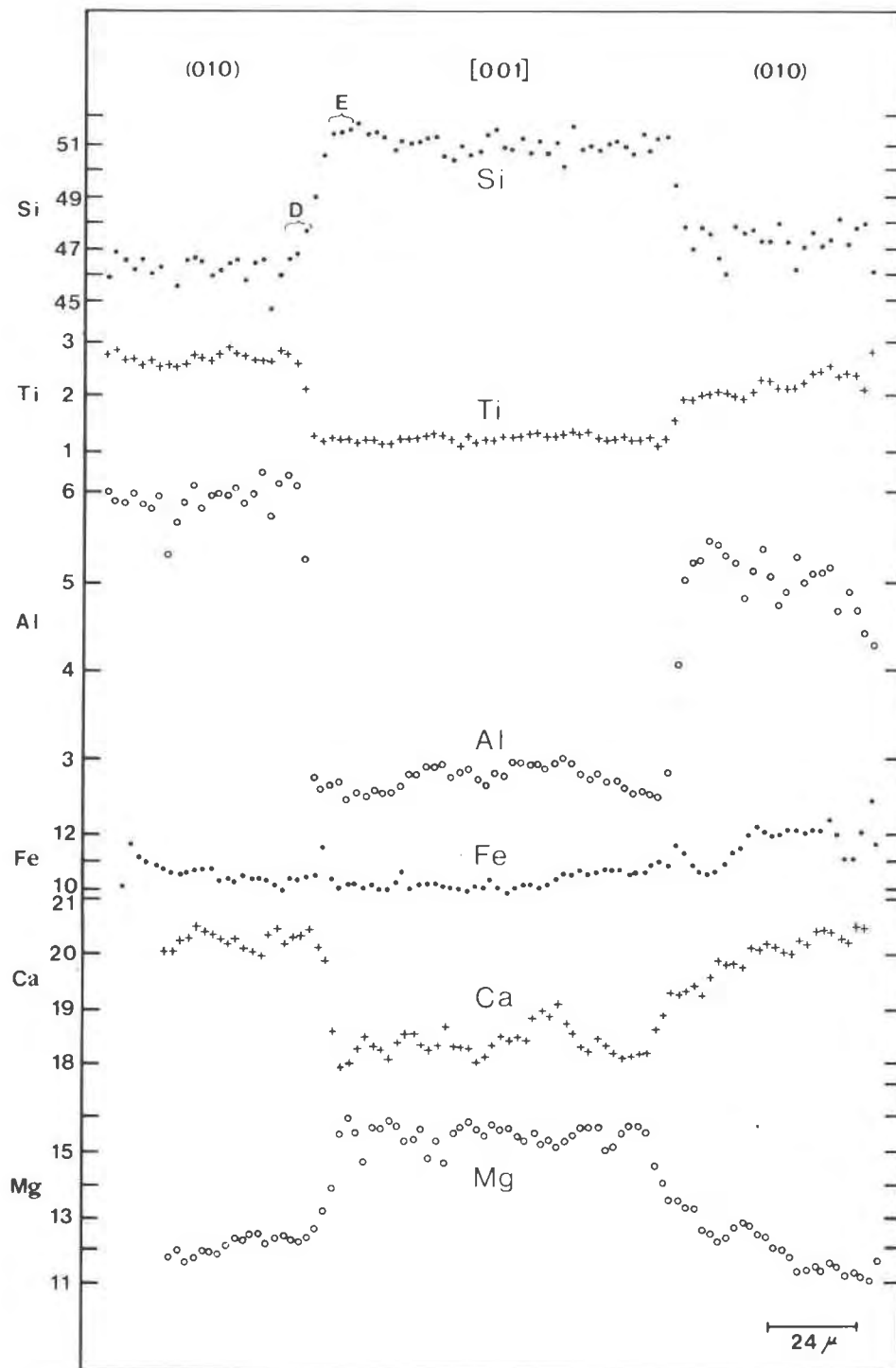


Fig. 3b. Variations of the elements Si, Ti, Al, Fe, Ca, and Mg along traverse (b), Fig. 1. Analysis points reported in Table 1 are identified by letters.

thin section is not precisely through the center of the crystal, a small portion of the sector whose base is parallel to the plane of the section is included in the section. Thus, in grain 1a the small central rectangle

is a slice of the apical portion of the (010) sector; in 1b it is (100).

The sector zoning was studied with the aid of an ARL-EMX electron microprobe using techniques

similar to those described in Hollister and Gancarz (1971). The augites have a fairly simple chemistry comprising the cations Fe, Ca, Mg, Si, Ti, and Al; (Cr, K, Na, and Mn were not found in detectable quantities). Representative analyses for sectors [001], (100), and (010) are presented in Table 1 with those of other studies for comparison. Although recognizably present, the small size of the (110) sector precluded accurate comparison with adjacent sectors.

Chemical variations between sectors are presented in Figure 3. Analyses made at two-micron intervals along the traverses illustrated in Figures 1 a and b show abrupt changes in concentration at sector boundaries for all elements except iron. Examination of Figure 3 and the table indicates that not all cations in other reported occurrences of sector zoning show the same relative enrichment with respect to sectors. This is most apparent in Ca: it varies between sectors in this study and that of Nakamura (1973), whereas it is constant in the crystals studied by Hollister and Gancarz (1971). On the other hand, differences in Ti, Al, and Si between sectors are large in all samples except that of Nakamura, which may be because the [001] sector is absent from Nakamura's sample. The big sectoral difference in Ca in the present example is between [001] and the other sectors, whereas for that of Nakamura it is between (100) and the other prismatic sectors.

Only terrestrial examples are given in the table. The lunar examples add more complexities.

It should be clear that any model for the origin of sector zoning must take account of the fact that there is not one universal pattern of sector zoning, even in one mineral. The model developed by Dowty (1976) comes the closest to explaining sector zoning for the few examples which have been described, but no model has yet accounted for differences of patterns of sector zoning in one mineral species.

Acknowledgments

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