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ANORTHITE FROM CALIFORNIA

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In the course of a petrologic study of the San Marcos gabbro,[1] in the San Luis Rey quadrangle, California, it was found that the olivine-bearing phases of the rock are composed predominantly of a plagioclase feldspar which falls well within the composition range of anorthite (94% An). Since a number of composition determinations by means of index liquids showed the calcic plagioclase to be remarkably uniform in its optical properties and since much of it is altogether free from zoning, this anorthite seemed to afford a favorable opportunity for obtaining accurate data to check the existing feldspar curves. The results of a study of the optical properties of this anorthite, together with chemical analyses of both the mineral and the rock in which it occurs, are given below.

The anorthite- and olivine-bearing gabbroid rocks are ordinary plutonic types belonging to the complex Peninsular Range batholith of southern California. They are associated in the San Marcos formation with other gabbroid rocks containing normal labradorite feldspar. The gabbroid rocks appear as a number of small irregular masses among the more prominent quartz diorites and granodiorites of the batholith. The olivine- and anorthite-bearing rocks are estimated to outcrop over an aggregate area of eight square miles within the San Luis Rey quadrangle. This quadrangle makes up the northwestern part of San Diego County. Similar anorthite-bearing rocks have been reported from adjoining portions of the batholith in San Diego County by Lawson,[2] Kessler and Hamilton,[3] and Hudson.[4]

[1] Miller, Franklin S., Petrology of the San Marcos Gabbro, San Luis Rey quadrangle, California, unpublished doctorate thesis, Harvard University, May 1934.

[2] Lawson, A. C., The Orbicular Gabbro at Dehesa, San Diego County, California: *Bull. Univ. Calif. Publ., Dept. Geol.*, vol. **3**, pp. 383–396, 1904.

[3] Kessler, H. H., and Hamilton, W. R., The Orbicular Gabbro of Dehesa, California: *Am. Geol.*, vol. **34,** pp. 133–140, 1904.

[4] Hudson, F. S., Geology of the Cuyamaca Region of California: *Bull. Univ. Calif. Publ., Dept. Geol.*, vol. **13**, pp. 175–252, esp. pp. 193–207, 1922.

The principal mineral constituents of the rocks are anorthite, olivine, hypersthene, augite, and hornblende. Through marked local variations in the proportions of these minerals the rocks range from olivine norite and olivine gabbro to troctolite and hornblende-olivine gabbro. There are also very small patches of anorthosite. All the rocks are dominantly feldspathic with anorthite amounting to more than 60 per cent by volume. The type which occurs most widely and which may be considered the average rock of the group is an olivine norite with notable hornblende, such as is represented by the analyzed specimen (354). Like the mineral composition, the grain size of the rocks shows striking variations over short distances from less than 0.5 mm. to more than 5.0 mm.; but the general texture and the composition of the plagioclase remain comparatively uniform.[5]

Analysis		Norm		Mode	
SiO_2	42.86	Or	0.56	Plagioclase	67
TiO_2	0.18	Ab	6.29	Hornblende	11
Al_2O_3	24.94	An	64.22	Hypersthene	2
Fe_2O_3	2.13	Di	0.68	Olivine	18
FeO	6.14	Hy	4.09	Iron Ore	0.2
MnO	0.06	Ol	20.09	Spinel	2
MgO	9.28	Mt	3.02	Iddingsite	0.2
CaO	13.08	Il	0.46		
Na_2O	0.76				100.4
K_2O	0.09		99.41		
H_2O	0.78	Normative		Modal	
S	0.03	Plagioclase		Plagioclase	
		91% An		94% An	
	100.33				

The rock (354) of the above analysis, norm, and mode is a typical hornblende-bearing olivine norite from the northwest end of the summit ridge of Pala Mountain at 2050 feet elevation (San Luis Rey quadrangle, California, topographic sheet). It is interesting because of its low silica content for an ordinary feldspathic gabbroid rock. In this respect it corresponds to many ultra-mafic rocks. Yet it differs from the type allivalites and eucrites of Harker[6] in its lower content of mafic minerals and less marked ultramafic affinities. The analysis was made by F. A. Gonyer in

[5] The details of the occurrence and relationships of these calcic plagioclase rocks will be described in a later paper.

[6] Harker, A., The Geology of the Small Isles of Invernessshire: *Memoir Geol. Surv. Scot.*, 210 pp, **1908**.

the laboratory of the Department of Mineralogy and Petrography at Harvard University. The mode is based on measurements with a modified Wentworth recording micrometer recalculated to weight percentages.

The anorthite occurs in nearly equant anhedral grains which show no crystal boundaries. The resulting allotriomorphic texture is designated "mosaic," employing that term in the same sense in

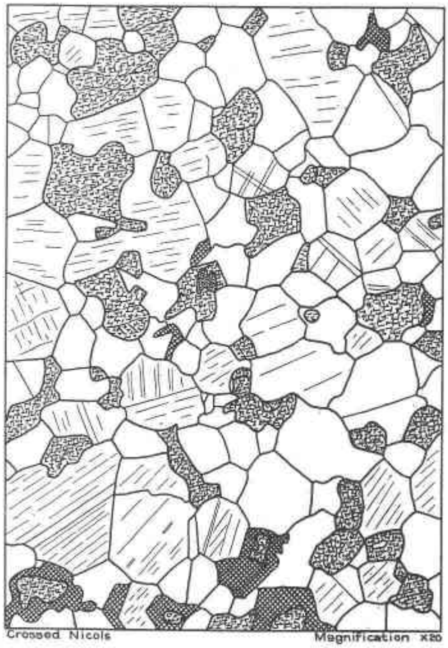

FIG. 1. Mosaic texture of the anorthite in an olivine-bearing phase (troctolite) of the San Marcos gabbro.

which it has been used by Graton and Murdoch[7] for the entirely similar textures of such minerals as pyrite in polished sections of the metallic ores. The mineral grains are bounded by straight or gently and regularly curving lines (as seen in thin section) which are independent of the crystal structure and which tend to give them polygonal shapes, such as might have been produced by the mutual interference of growing crystals (Figure 1). The boundaries

[7] Graton, L. C., and Murdoch, J., The Sulphide Ores of Copper. Some Results of Microscopic Study: *Trans. Amer. Inst. Min. Eng.*, vol. **45**, pp. 26–93, p. 36, 1914.

of three contiguous grains often meet at a triple point; occasionally the boundaries of four grains meet at a quadruple point. The grains are all of the same order of size, so that the texture is equigranular. Olivine, augite, or hornblende at times enter into the mosaic along with the anorthite.

The term "mosaic" has sometimes been used as roughly synonymous with "granulitic" in the sense of the latter word advocated by the committee on British petrographic nomenclature.[8] It is so listed in the standard handbooks,[9] but without any citation of an original or specific definition. The term granulitic itself has been employed in two different senses, one, following the original definition by Judd in 1886, equivalent to the "intergranular" of Evans and the other, following Michel-Levy and the usage recommended by the British committee, for "rocks characterized by even-sized and closely-fitting grains." Even in the latter sense "granulitic" is not strictly synonymous with "mosaic" as here defined and appears to be more applicable to metamorphic than to igneous rocks. It is suggested that "granulitic" be restricted to textures of metamorphic rocks, whether of igneous or sedimentary origin, and that "mosaic" be used for the truly primary texture of igneous rocks which corresponds to that described by Graton and Murdoch in the metallic ores.

Such a mosaic texture of the anorthite plagioclase is characteristic of the olivine-bearing rocks and distinguishes them from the other gabbroid rocks of the San Marcos formation. It is best developed in the rocks with the least hornblende. When any large amount of hornblende is present, there is a tendency for the plagioclase to show moderate zoning, to have a slightly less calcic average composition, a bytownite-anorthite with 87–92 per cent An, and to form thick tablets (parallel to (010)) with more or less definite crystal boundaries.

The anorthite, then, occurs in nearly equant anhedral grains. The grains are remarkably fresh and clear and free both from alter-

[8] Watts, et al., Report of the Committee on British Petrographic Nomenclature, *Mineral. Mag.*, vol. **19**, pp. 140–141, 1921

[9] Holmes, A., *The Nomenclature of Petrology*, 2nd Edition, London, Thomas Murby, 284 pp., p. 162, **1928**.

Grout, F. F., *Petrography and Petrology*, New York, McGraw-Hill, 522 pp., p. 42, **1932**.

Johannsen, A., *A Descriptive Petrography of the Igneous Rocks*, Chicago, Univ. of Chicago Press, vol. 1, 267 pp., p. 220, **1931**.

ation products, such as kaolin and sericite, and from inclusions of any sort. Zoning is practically absent in the majority of the specimens. Several grams of the anorthite were separated from the powdered rock remaining from the chemical analysis (354) by the following process. The powder was ground to pass a 200-mesh screen. The fine dust which failed to settle in a beaker of water within about a minute was decanted off. As much of the mafic material as possible was removed by exposing the remaining powder to a strong electromagnet, and the powder was further purified by gravity separation with bromoform. All the other rock minerals were heavier than the anorthite and settled readily in a liquid with a specific gravity of 2.80. The separation was repeated several times, until a clean anorthite concentrate was secured, the gravity of the liquid being varied to remove mixed grains. Under the microscope less than 1 per cent of the grains showed any trace of attached extraneous material. The total amount of such material, chiefly hornblende, was only a few tenths of a per cent. The powder was analyzed by F. A. Gonyer.

Analysis		Molecular Numbers	Norm	
SiO_2	43.77	.730	Or	0.56
Al_2O_3	36.11	.354	Ab	5.76
Fe_2O_3	0.09	.001	An	93.13
MgO	0.07	.002		
CaO	18.73	.335		99.45
Na_2O	0.67	.011	Recalculated to 100%	
K_2O	0.11	.001	gives 93.6 or 94% An.	
H_2O	0.40			
	99.95			

The computation shows the analysis to have a slight deficiency of silica and a slight excess of alumina as compared with lime and the alkalies. Calculation of the plagioclase composition on the basis of the ratio of Al_2O_3 to SiO_2 alone gives 95 plus per cent An. The average of the two methods of calculation is nearer to 94 per cent An.

The principal physical and optical properties of the mineral, determined from the powder and the thin sections, may be summarized as follows:

Twinning according to the albite, pericline, and Carlsbad laws is prominent in many grains but is much less common than in most plagioclases. The twin lamellae of the polysynthetic types are generally thicker and less numerous than in plagioclases of intermediate composition. In a number of thin sections less than half of the grains show any twinning, and this can be attributed only in small part to the orientation of twin planes parallel to the sections. The albite twinning is the most widespread type. The combination of albite and pericline twinning is very common. Carlsbad twins are rather rare. Other less common types of twin-

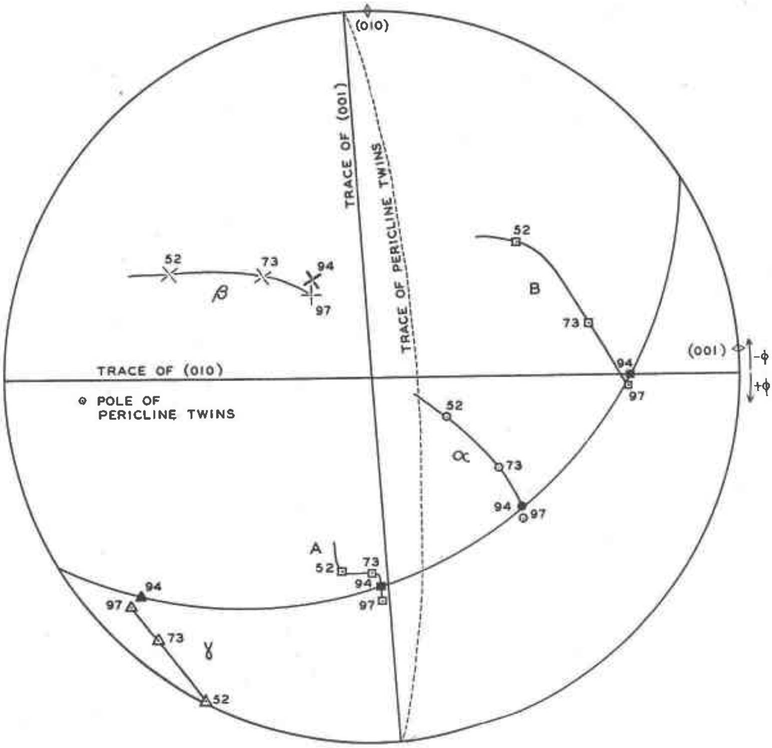

Fig. 2. Stereographic projection on the plane normal to the (001) and (010) cleavages. The ellipsoidal axes and the optic axes of the anorthite containing 94% An are plotted together with those of Duparc and Reinhard's calcic plagioclases.

ning may be present; but these can only be identified with the universal stage, and they did not appear in the dozen grains which were studied on the stage.

Both the (001) and (010) cleavages are well developed, but the (001) cleavage is the more perfect of the two. The cleavage angle is 86°. The specific gravity is 2.759.

Optical Properties:

Refractive indices:	$\alpha=1.574$
	$\beta=1.582-$
	$\gamma=1.586+$
Birefringence:	$\gamma-\alpha=0.012+$
Optical character	Negative
$2V$	79°
Dispersion	$r<v$ (distinct)

The optical orientation is evident in figure 2, a stereographic projection after Duparc and Reinhard[10] on the plane normal to the (001) and (010) cleavages. The determined ϕ and ρ values for the principal optical directions of the 94 per cent An plagioclase are listed below. The right-hand side of the trace of (010) is taken as the zero position for ϕ, $+\phi$ being read 180° clockwise and $-\phi$ 180° counterclockwise. (ρ is measured outward from the center of the projection along the ϕ direction.)

	ϕ	ρ
α	+ 42	57
β	−121	34
γ	+137	82
Optic axis A	+ 88	60
Optic axis B	0	70
Pole of (010)	+ 90	90
Pole of (001)	− 4	90
Pole of pericline twins	+176	76

The principal extinction angles calculated from the stereographic projection by Fresnel's construction are:

On (001)	$\alpha' \wedge (010)$	−35
On (010)	$\alpha' \wedge (001)$	−37
⊥ (001) and (010)	$\alpha' \wedge (010)$	+44
" "	$\alpha' \wedge (001)$	+42
⊥ α	$\beta \wedge (010)$	+35
	$\beta \wedge (001)$	−19
⊥ β	$\alpha \wedge (010)$	−40
	$\alpha \wedge (001)$	+38
⊥ γ	$\alpha \wedge (010)$	−50
	$\alpha \wedge (001)$	−65

The maximum extinction angle in the zone normal to (010) was measured on the universal stage as 53°.

[10] Duparc, L. and Reinhard, M., La Determination des Plagioclases dans les Coupes Minces: *Societe de Physique et d'Histoire Naturelle de Geneve*, vol. **40**, pp. 1–149, 1924.

The refractive indices were first determined by the immersion method with liquids differing by 0.005. Then special liquids were made up to match each of the indices, and these liquids were checked with the Abbe refractometer. Sodium light was used throughout. The value for the optic angle represents the average of six measurements with the universal stage. The results varied from 78 to 81°, but three of the best measurements fell at 79° to the nearest degree. The optical orientation was also obtained by averaging several measurements on the universal stage. The results were found to differ systematically from the curves of Duparc and Reinhard in the directions indicated by the points plotted for 94 per cent An in Figure 2.

A number of other extinction angles were measured directly on the universal stage, in addition to the maximum extinction angle in the zone normal to (010), and in most cases these agreed with the calculated angles within a few degrees. However, it was not found practicable to measure directly all the angles listed above and difficulty was experienced in finding grains which were accurately enough oriented for satisfactory measurements, without a complete orientation of the grain on the universal stage. This is particularly true of the commonly used angle on a basal section measured to the (010) cleavage. The values of this extinction angle vary so rapidly with slight errors in orientation that it is of little use in determinative work.

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