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FLOW-LAYERING IN ALPINE PERIDOTITE-GABBRO COMPLEXES[1]

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ABSTRACT

Compositional layering in gabbro and peridotite may originate in several ways; in alpine complexes most of it is believed to be flow layering. Disruption of relict primary features formed by crystal settling shows that the flow layers are later.

The flow layers in alpine complexes are not nearly as regular and persistent as those formed by crystal settling in the stratiform complexes, and adjoining layers commonly show much more compositional contrast. Features formed by crystal settling have been observed only as rare relicts in chromitites, and poikilitic and ophitic textures are not common. Tectonite fabrics have been described in alpine dunites from many localities, and gneissic structures are common in related gabbroic rocks. Foliation and lineation are closely related to layering and are mostly parallel to it, but in places they cross it. Boudinage in mafic layers and related structures in chromitite bodies show stretching.

The flow structures in alpine mafic complexes are directly comparable to those seen in other flow-banded intrusives and in high-grade metamorphic rocks. Flow layering, foliation and lineation cross the boundaries between rocks such as chromitite, dunite, harzburgite and gabbro without deviation. The predominant parallelism of layering with foliation and lineation is attributed to extensive flowage of largely crystalline magma during emplacement. Several lines of evidence show that the flowage features could not have been imposed on solid rock by regional deformation.

INTRODUCTION

Layering in intrusive rocks of gabbroic to peridotitic composition may originate in several ways. The layers in lopolithic stratiform complexes (Brown, 1956; Cameron and Emerson, 1959; Hess, 1960; Jackson, 1961) and in parts of some concentrically zoned intrusives (Ruckmick and Noble, 1959; Taylor and Noble, 1960; Irvine, 1963) are generally believed to have been formed by settling of crystals from fluid magma. Fractional crystallization that does not involve crystal settling accounts for layering in many dikes and larger intrusions. Flow-layering is a widely recognized phenomenon in lavas and intrusive rocks (Balk, 1937), and is believed to be the principal kind found in alpine peridotite-gabbro[2] complexes.

The alpine mafic complexes consist of gabbro and peridotite in all proportions, are irregular in form and structure, and occur along eugeosynclinal belts that have undergone an alpine type of deformation. Various features of alpine mafic rocks have been described in detail in many places by many geologists (Guild, 1947; Hiessleitner, 1952; Smith, 1958; MacKenzie, 1960; Wells *et al.*, 1949), and the critical features have been summarized previously (Thayer, 1960). Tectonite fabrics are now recognized as characteristic of many alpine peridotites (Turner, 1942; Lacroix, 1943; Marinos and Maratos, 1957; MacKenzie, 1960), and have also been described in some gabbroic rocks (Bartrum and Turner, 1938; Thayer, 1942; Stoll, 1958; MacKenzie, 1960). This paper describes features in both gabbro and peridotite that are comparable to phenomena in gneisses (Balk, 1937) and can be ascribed only to flowage in a semi-solid state. Except where explicitly stated otherwise, the discussion that follows is concerned only with alpine peridotite and gabbro.

The descriptions and conclusions in this paper are based principally on personal observations over several years in the United States and Cuba; on visits to the Philippines, New Caledonia and New Zealand in 1959; and to Yugoslavia, Greece, Turkey, Iran and Pakistan in 1960. Discussions with C. E. Brown, D. L. Rossman, P. W. Guild and F. G. Wells, in the field and in the office, have led to recognition of the features characteristic of alpine mafic rocks. Because of his intimate knowledge of the Stillwater Complex, E. D. Jackson has been especially helpful and stimulating in relating the features and evolution of alpine peridotites to those of stratiform complexes.

PRIMARY LAYERING

Unequivocal relict textures and structures that antedate flow-layering in alpine mafic rocks have been identified only in chromitites, especially in large massive ore bodies. Mesh textures formed by fine-grained euhedral chromite interstitial to large olivine crystals, mixed large crystals and nodules of chromite in dunite or troctolite (Thayer, 1942, Pl. 4),

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[2] For convenience the gabbroic and peridotitic rocks are referred to collectively as mafic.

FIG. 1. Parallel flow-layering in peridotite and gabbro. Note thin layers at upper right. Canyon Mountain, Grant County, Oregon.

trbicular structures in chromite and dunite (Wells ond others, 1949, Pl. 10, 11), and some dunitic and aroctolitic layers in massive chromitite (Guild, 1947, p. 231) appear to have been formed by variations of the crystal settling mechanism. Descriptions of these structures in various stages of mechanical disruption are numerous in the literature on chromite. The competence of the chromite relative to associated silicates apparently preserved the original or primary textures and structures. These relict features imply that the alpine complexes essentially are partially refused and remobilized parts of huge settled complexes formed deep in the crust or mantle. I suggest, therefore, that the term "primary" be restricted in alpine complexes to relict layers or features comparable to those in known stratiform complexes.

Parallel Flow-layering, Foliation and Lineation

In most exposures flow-layering in gabbro and peridotite (fig. 1) appears parallel and uniform over strike distances of tens or hundreds of feet. In relatively small exposures (Fig. 2) the layers may seem remarkably uniform and clearly defined. Careful examination usually reveals, however, that the layers are lenticular and pinch or grade out in a few feet or tens of feet; their lateral extent does not compare with the persistence of layers in stratiform complexes.

Flow-layers may be monomineralic as well as polymineralic. The individual layers in a given series may differ widely in composition and occur in any order. Dunite, anorthosite and pyroxene gabbro, for example, may be intimately interlayered in a manner never seen in stratiform complexes. The boundaries between layers may be sharp or gradational (Fig. 2) and change along the strike. The texture of the rocks is xenomorphic granular (Stoll, 1958, p. 424), and in hand specimen the gabbroic varieties resemble high-grade metamorphic gneisses (Stoll, p. 426). The average grain size varies widely, ranging from about a millimeter to 10 cm in pegmatitic layers (Fig. 3). The textures of the pegmatitic layers in outcrop resemble the textures of fine-grained layers in thin section.

Foliation and lineation characterize flow-layers (Figs. 2, 3). Foliation, shown by planar orientation of individual grains or clusters of grains, and layering intergrade to an extent that presents frequent problems in mapping. Lineation, shown by arrangement of mineral grains in lines, is present more commonly than not. Lineation and foliation may occur together or independently in unlayered rocks. Poikilitic, diabasic and cuspate textures, which characterize many rocks in stratiform complexes (Jackson, 1961, p. 23), are rarely found.

The textures and structures in chromitites correspond directly to those in the silicate rocks, although they are expressed somewhat differently. Layering of chromite, olivine and mixtures of the two minerals in all proportions is prominent in many chromite deposits, and remarkable lineation and boudinage occur in some (Guild, 1942; Wells *et al.*, 1949). In many chromite deposits lineation is shown by elongate lenses of dunite in chromite (Fig. 4), or the reverse. The chromite uniformly is anhedral, crystals being rare, and stretching (pull-apart texture) is shown by rude orientation of the wider intergrain silicate seams (Stoll, 1958, Pl. 3, Fig. 3) normal to the axis of lineation. In massive ores pull-apart texture may be the only indication of lineation.

Layers covering the entire range in composition

FIG. 2. Parallel foliation in interlayered gabbro and peridotite. Note sharp contact between anorthositic and peridotitic layers in left edge of block. Canyon Mountain, Grant County, Oregon.

FIG. 3. Gneissoid pegmatitic hypersthene gabbro interlayered with olivine-rich peridotite (left). Compare texture with that of dike in Fig. 10. Canyon Mountain, Grant County, Oregon.

FIG. 5. Lineation crossing pyroxenite layer in gabbro. Axis of lineation is parallel to knife, which is about 4 inches long. Canyon Mountain, Grant County, Oregon.

from chromitite and dunite to anorthositic gabbro show similar behavior in folding. All layers characteristically thicken at the crests of simple folds, and boudinage is developed in the more mafic layers and in chromitites (Wells *et al.*, 1949; Guild, 1942). Nearly all varieties of folds may be found, from open (Fig. 8) to tight and complex (Fig. 9).

DISCORDANT FLOW-LAYERING, FOLIATION AND LINEATION

Discordances between flow-layering on the one hand and foliation and lineation on the other provide clues to complex variations in magmatic movements during emplacement. Foliation oblique to unfolded layering in peridotite has been described in Cuba by Guild (1947, p. 232). This and several other aspects of discordant foliation and lineation are shown in Figs. 5 to 9. Figure 5 shows lineation obliquely crossing interbanded gabbro and pyroxenite. Analogous discordant structural relations in layered gabbro (Fig. 6) and chromitite in peridotite (Fig. 7) show that both have undergone the same kind of deformation. The layered gabbro in figure 6 shows good line-

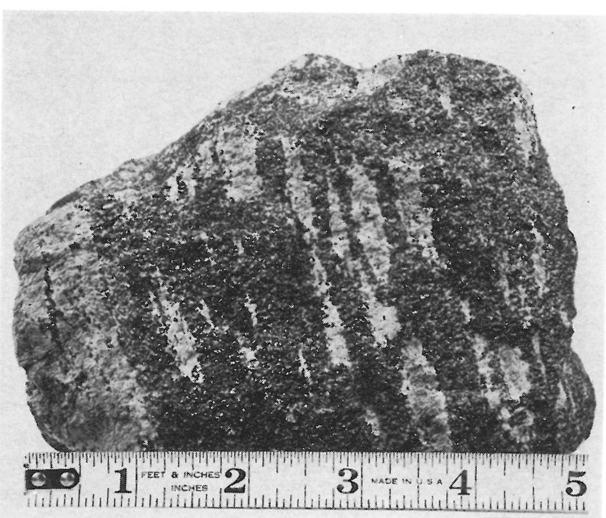

FIG. 4. Elongate lenses of serpentinized dunite in anhedral chromite. Pulling apart of chromite (pull-apart texture) during differential flow of dunite is shown by rudely oriented fractures normal to axis of lineation. Coto Mine, near Masinloc, Luzon. Scale in inches.

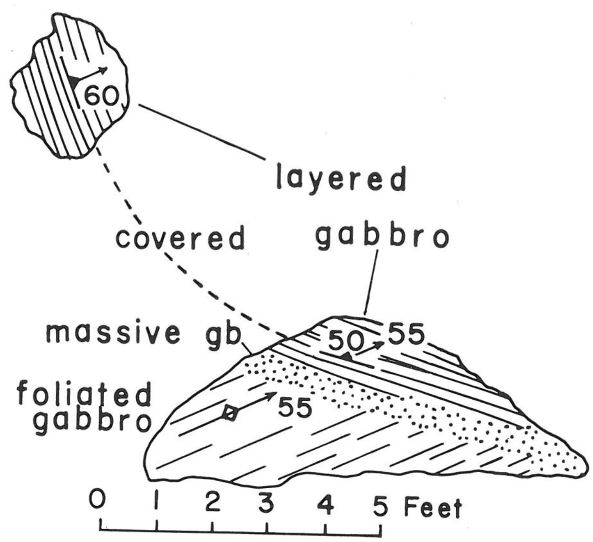

FIG. 6. Map showing relations of lineation that plunges uniformly 55°–60° NE., to layering and vertical foliation in gabbro. In the smaller outcrop lineation parallels the layering, but in the larger it strikes obliquely across and plunges steeper than the layering dips. Canyon Mountain, Grant County, Oregon.

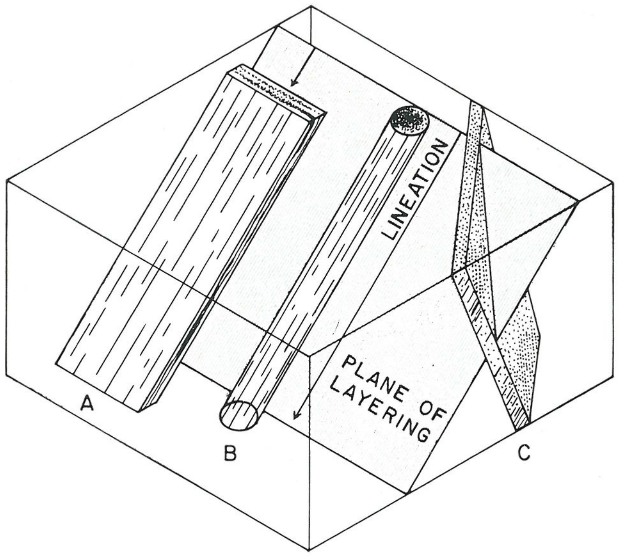

FIG. 7. Diagram showing relations of three types of chromite deposits to plane of layering and lineation in host rock peridotite: A, Extensive tabular; B, fusiform; C, crosswise. Banding is shown by solid lines on surfaces parallel to the axis of lineation and by rows of dots on surfaces oblique or normal to it, to indicate the relative evidence in corresponding outcrops.

ation; in the smaller exposure the lineation plunges directly down the dip, but in the larger one it plunges obliquely across the layers more steeply than the dip. The vertical foliation in the larger outcrop is prominent and the lineation is alined precisely within it. Massive gabbro with indeterminate contacts occupies a zone 6 to 12 inches wide between the foliated and layered facies; it appears to be material in which the layering was destroyed and new foliation was not developed. Nearby gabbro exposures show only the lineation. Chromite deposit C in Fig. 7 lies across the layering in the host rock peridotite but shows internal lineation and foliation in the plane of the peridotite layering, just as the two accordant deposits do. The contact relations, textures, and composition of the chromite in all three types of ore bodies may be identical. For example, the 10 million-ton Coto (Masinloc) deposit (Stoll, 1958), nearby ore bodies on Reservation Number 1 (Rossman *et al.*, 1959, p. 6) and two major ore bodies at the Acoje mine in Luzon Philippine Republic, show "crosswise" relations, whereas most of the large ore bodies at Acoje are accordant (D. L. Rossman, written communication, 1960). At Coto the chromite is anhedral (Stoll, 1958, p. 437), the chromite ore body is surrounded by a halo of dunite, and the long dimension of the ore body extends about 1800 feet across the layering in the host rock peridotite. Lineation in the ore, however, is alined with the plane of the layering in the peridotite.

In some places two episodes of deformation separated by intrusion of dikes are suggested, as for instance, by the rocks shown in Figs. 8 and 9. The two figures show three sides of one outcrop. Figure 8 shows three sharply bounded dikes, the middle one only about half an inch thick, of plagioclase- and olivine-bearing pyroxenite crossing an open fold in layered olivine gabbro. Some of the layers in the gabbro are only 1 or 2 mm thick. Two of the dikes follow a strong foliation; the third widens irregularly and crosses the foliation. All the dikes show the same strong lineation that plunges steeply down the axis of the fold in the olivine gabbro, and shows in the right side of the view. Figure 9 shows complex folding in an anorthositic layer exposed on a joint face across the foliation and lineation. The foliation in the lower part of the view approaches layering in its development and parallels layering in nearby outcrops.

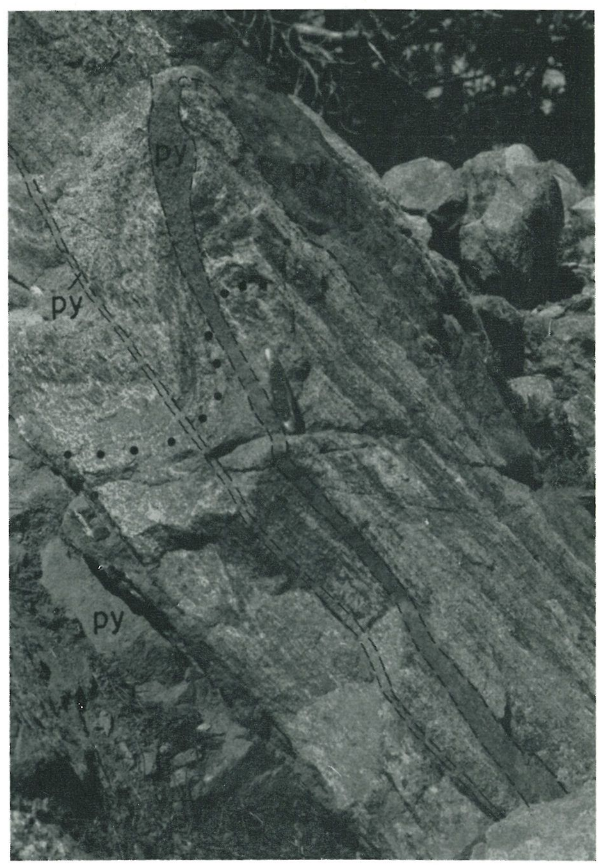

FIG. 8. Dikes of pyroxenite (py) crossing folded layers (line of dots) in olivine gabbro. All of the rocks show the prominent lineation seen on the right-hand face of the outcrop. View downward from northeast toward upper corner (marked by knife) of outcrop; compare with Fig. 9. Canyon Mountain, Grant County, Oregon.

FIG. 9. Thickening of anorthositic and mafic layers in gabbro along crest of relict fold in foliated and lineated olivine gabbro. The lineation plunges parallel to the axes of the folds. View of part of vertical joint face on south side of the outcrop shown in Fig. 8.

In thin section the dikes and gabbro alike show deformation lamellae in olivine, undulatory extinction and disruption in clinopyroxene and plagioclase and granulation along grain boundaries.

Relations of Flow Structures to Major Rock Units

The relations of flow layering, foliation, and lineation in alpine mafic rocks are directly comparable to metamorphic structures in sedimentary rocks. In contrast to primary layering in stratiform complexes, which controls and parallels the distribution of the various rocks, flow layering consistently crosses the boundaries between major rock units. The relations of layering to chromitite, saxonite, dunite, and gabbro in the vicinity of the Coto mine in the Philippines are described by Rossman *et al.* (1959) as follows:

"Field work has shown that the layered structure, but not necessarily individual layers, extends across lithologic boundaries without deviation. Thus there does not appear to be any correlation between the attitude of the contacts and the attitude of the layered structures. . . . (p. 5). [Layering] shows no recognizable control over the shape or location of the chromite. The ore deposits are typically irregular in shape but the layered structure in the enclosing rocks is homoclinal and remarkably uniform." (p. 6)

Dikes

Although some irregular pegmatitic masses and dikes show deformation like that in Fig. 3 to various degrees, undeformed gabbro dikes are common features in many alpine complexes, even where large masses of gabbro are not known. The gabbro dikes shown in Fig. 10 are typical; they cross obscure and irregular structure in feldspathic peridotite. The wide range and abrupt changes in grain size match the textures described in Cuba by Guild (1947, p. 228) and Thayer (1942, p. 24). Most dikes are sharply bounded by matching walls, show no chilling at the borders, and cut at random across flow structures and other boundaries between lithologic units.

Discussion

Practically all the layering we see in alpine mafic rocks is believed to be flow-layering. The prevalence of foliation and lineation, cross-cutting relations of layered structures across major lithologic boundaries, random distribution of rock types, great lithologic contrast between adjoining layers, and lack of cryptic layering (Wager, 1953) are completely at variance with the normal relations of primary layers in stratiform complexes. Obvious disruption of primary features where found, comparatively rarely, in competent chromitite masses shows that the flow structures are later. The prevailing parallelism between layering, foliation, and lineation, and especially the

FIG. 10. Branching dikes of medium-grained and pegmatitic gabbro crossing rude banding in feldspathic peridotite. The hammer lies on an irregular band of olivine-rich peridotite. Canyon Mountain, Grant County, Oregon.

common gradations between layering and foliation, show that the layering and other flow structures are closely related genetically.

In some places two generations of flow structures can be recognized, both apparently unrelated to any primary layering. The olivine-rich nature of some of the gabbroic layers in Figs. 6 and 8, for example, indicates that they are not primary; because any textural criteria would have been obliterated by flowage, compositional variation is of utmost importance. The cross-cutting relations of foliation show that it is younger than the layering in both figures. The crosswise chromite deposits, likewise, are believed to be relatively competent relict masses that were oriented in one direction by early flowage and deformed by later flowage from another direction. It would seem, furthermore, that good compositional layering can be developed in peridotite and gabbro, while lineation only is formed in chromitite under similar conditions.

Several lines of evidence show that the flow structures were developed under magmatic conditions during emplacement. All the features described have been found in fresh or only slightly altered rocks, which commonly are cut by dikes of dunite, peridotite, or gabbro. There is little correlation between development of flow structures in the mafic rocks and metamorphic grade of the country rocks; some of the best layered complexes are in unfoliated terranes. The many consistent differences between alpine and stratiform mafic rocks (Thayer, 1960), including composition (Hess, 1938), cannot be explained by tectonic disruption and regional metamorphism of stratiform rocks (Helke, 1962).

The dikes show a complex magmatic history. Most dikes, whether of dunite or gabbro or intermediate composition, are undeformed. Because the dikes are limited to the mafic plutons and gabbroic types are by far most abundant, they are believed to have been generated locally by movement of interstitial rest magma into fractures. Their generally undeformed nature, accordingly, implies that flowage of the rocks as a whole ceased before consolidation of the rest magma. In eastern Oregon, however, some pegmatitic gabbro dikes and small intrusive masses show all degrees of deformation up to that shown in Fig. 3; it seems clear that there dike-intrusion and magmatic flowage overlapped considerably. The relations in Figure 8 suggest that layering may have been formed partly by extensive deformation of dikes intruded along foliation.

The evidence seems conclusive that in alpine complexes gabbroic as well as peridotitic rocks were emplaced as semisolid crystal mushes in which the ratio of solids to liquid was too high to permit crystal settling, even of coarse-grained chromite. The rarity of relict primary features implies that practically all of the layering we see was formed during emplacement, perhaps partly by remixing of predifferentiated rocks, and partly by processes akin to metamorphic differentiation. The aggregate movement by flowage must have been several kilometers, and may have been several tens of kilometers.

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