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By
DONAL M. RAGAN

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EMPLACEMENT OF THE TWIN SISTERS DUNITE, WASHINGTON

DONAL M. RAGAN

Geology Department, University of Alaska, College, Alaska

ABSTRACT. The large, elliptical, 36-square-mile Twin Sisters dunite and two smaller dunite bodies are located along a northwest-trending, nearly vertical fault and are intrusive into several thrust plates and locally into the unconformably overlying Swauk formation. The time of emplacement was post-Paleocene, and definitely later than the main Cretaceous orogeny.

The Twin Sisters mass is composed of a virtually unaltered, coarse-grained enstatite-bearing dunite, with accessory amounts of chromite and chromium diopside. Every section displays abundant evidence of cataclasis, including granulation and bending of mineral grains, and translation bands in olivine. Completely identical textures have recrystallized. These recrystallized cataclastic features now consist of fine-grained, unstrained olivine mosaic zones surrounding and embaying large, strained porphyroclasts. Locally thin mosaic zones cut single, large crystals. The translation bands have recrystallized into bandlike forms with irregular, sutured boundaries. This recrystallization is thought to have taken place at moderate temperatures.

Serpentinites are marginal to and gradational with the large Twin Sisters mass and one exposed smaller body. The width of this narrow marginal zone is essentially the same for both the large and the small, and is thus independent of the size of the mass. In detail, there is an outward transition from unaltered dunite to partially serpentinized dunite to massive serpentinite and finally to schistose serpentinite at the actual contact. Serpentine is very rare in the core area.

It is concluded that the Twin Sisters dunite mass moved and deformed while still hot enough to recrystallize (possibly during the intrusive rise), later by cataclasis alone. Near the last stages of emplacement serpentinizing fluids were added from the country rock to the marginal portions. This reduced friction at the contact, and further intrusion was accomplished by marginal faulting.

INTRODUCTION

The origin and mode of emplacement of alpine-type peridotites and their role in the orogenic cycle are longstanding problems. Concerning their condition during emplacement two general schools of thought have emerged. For convenience these can be called the "hot-wet-liquid" and the "cool-dry-solid" points of view. The question is which is more nearly correct? Hess (1955, p. 402), in a recent summary, succinctly states the present status of the work: " . . . the problem remains unsolved. Some vital piece of evidence is still missing."

What is attempted here is the presentation of evidence concerning the mode of emplacement of one large peridotite body. This evidence helps to overcome some of the previous difficulties. With modifications the results are in general agreement with the ideas of Bowen, the main proponent of the "cool-dry-solid" school.

CASCADE PERIDOTITES

A number of scattered peridotite and serpentinite masses have been mapped in the northern and western parts of the Washington Cascades. The larger of these are shown on the new Geologic Map of Washington (Huntting, and others, 1961).

The largest single peridotite mass in this area is located in the Twin Sisters Range, a part of the mountainous western flank of the Cascades of

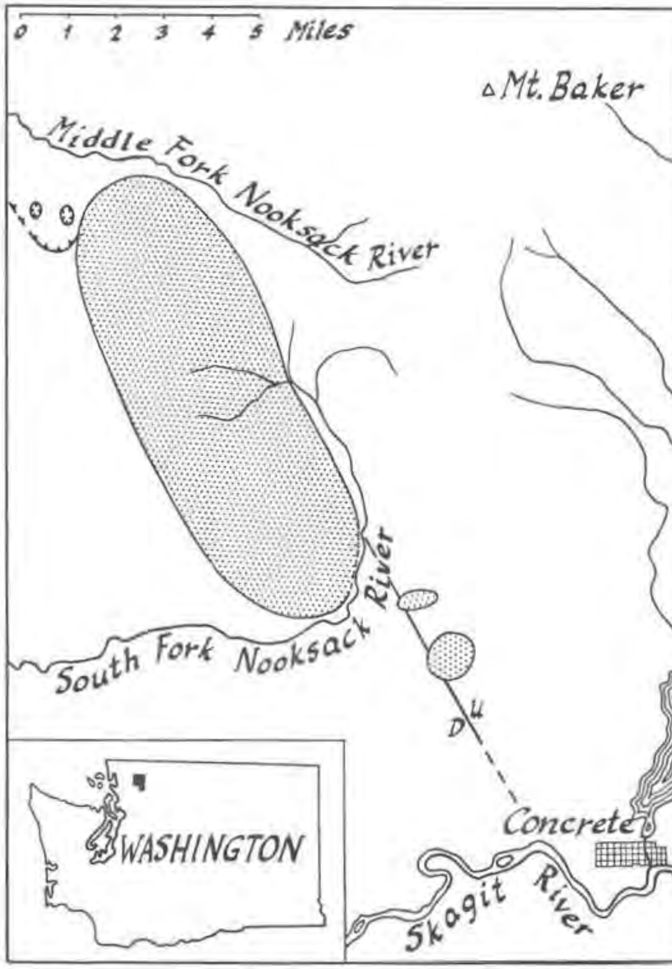


Fig. 1. Index map showing the location and tectonic position of the large Twin Sisters dunite and two smaller dunite bodies. The area to the east and north of the dunite masses is underlain by the rocks of the middle or Church Mountain thrust plate; to the west the rocks compose the overlying or Shuksan thrust plate.

northwesternmost Washington. It is located about 60 miles north of Seattle and 20 miles due east of Bellingham (fig. 1). The Twin Sisters dunite, one of the large dunite bodies of the world, has been known for some time. It is somewhat inaccurately located, and shown as a Mesozoic (?) basic intrusive on the old geologic map of the state (Culver and Stose, 1936). Bennett (1940) briefly described the dunite and some of its internal features. Cater, and others (1941) in a brief description of some chromite claims gives an accurate but small scale map of the body. Misch (1952) mapped the northwest corner of the mass. Thayer (in Ross, Foster, and Myers, 1954, p. 705) briefly describes the dunite and its petrology, and specimens collected in part by him have been subsequently analyzed in various ways by others. Recently I reported some preliminary conclusions concerning the mode of emplacement (Ragan, 1959).

GEOLOGIC SETTING OF THE TWIN SISTERS DUNITE

Misch has extensively studied the area to the north and east of the Twin Sisters Range. Structural units mapped by him were, in part, extended into the areas surrounding the dunite mass during the present study. Following Misch (1960) three main structural units are recognized, each separated by a major thrust. The lowest unit, considered autochthonous, is composed of the Jurassic-Cretaceous Nooksack formation. Over this, the Church Mountain thrust brings rocks of the upper Paleozoic Chilliwack group and associated formations. The upper thrust brings presumably pre-Jurassic phyllites, blueschists, and greenschists over the Chilliwack and associated rocks. The lowest unit is exposed in a window north of Mount Baker, and the middle unit is an elongate, complex half-window, which extends for about 50 miles from near the Canadian border to south of Darrington in the Sauk River area. This large half-window and the bordering, anticlinally deformed upper or Shuksan-Whitechuck thrust is one of the dominant structural features of the western part of the Northern Cascades.

In an irregular northwest-trending belt across the Cascades, the Swauk formation of uppermost Cretaceous-Paleocene age overlies these thrusts and associated structures with marked angular unconformity. This formation has in turn been strongly folded and in places cut by high angle faults.

The Twin Sisters dunite and two smaller dunite masses are located along the contact between phyllite of the upper or Shuksan thrust plate and the Chilliwack group rocks of the next lower or Church Mountain thrust plate, at the western edge of the complex half-window. In this area the contact is practically vertical and is interpreted to be a fault along most of its length. This fault was first mapped by R. W. Jones (1959, Geology of the Finney Peak area, Northern Cascades of Washington, unpublished Ph.D. thesis, University of Washington) in the adjacent area south of the Skagit River, and named the Sutter Mountain fault. The location, trend and elongation of the dunite bodies corresponds to the fault. The large Twin Sisters mass is also locally intrusive into the overlying Swauk formation.

PERIDOTITES OF THE TWIN SISTERS RANGE AND VICINITY

The Twin Sisters dunite and the two newly found smaller dunite bodies are almost identical lithologically. In addition, seven small pod-shaped serpentinite bodies are located nearby; these are identical to marginal serpentinite phases of the dunite.

The Twin Sisters dunite body is an elliptical mass ten miles long and four miles wide, with a total area of about 36 square miles. It forms the entire Twin Sisters Range. Dunite is exposed vertically from elevations of about 1500 feet to almost 7000 feet, the highest point in the range. Above a very low timberline (Ragan, 1961) exposures are perfect. With the exception of one locality, the contacts, however, are only poorly exposed. Because it is the largest, most accessible, and best exposed, the Twin Sisters mass is described in greatest detail.

Petrology

The rock of the Twin Sisters body (and the two other masses) is typically a medium- to coarse-grained, enstatite-bearing dunite. It weathers to a distinctive light reddish brown (dun) color.

The amount of enstatite generally varies from zero to about 20 percent in the body. Very rarely small irregular pods and dikelike masses contain up to 100 percent enstatite. The pure olivine dunite and the enstatite-bearing types (including saxonite) have been reported to be interbanded (Bennett, 1940). For the whole body I was not able to verify this. Instead enstatite was found to be more or less generally distributed throughout the body.

Except for the marginal serpentinite zone, Thayer (in Ross, Foster, and Myers, 1954, p. 705) estimates that saxonite (10 to 20 percent enstatite) forms two-thirds to three-fourths of the mass, and pyroxene-rich peridotite 5 percent or less. The remainder is pyroxene-free dunite. Estimates based on the present study indicate that enstatite is less abundant. Dunites with no enstatite or with only a trace may form as much as 50 percent of the body. However, sampling was neither systematic enough nor complete enough to justify a statistically valid estimate of the composition of the entire 36 square miles at this time.

Mineralogy

Universal stage measurements of optical angle (usually only one axis was within the limit of rotation), estimates of interference figures, and one refractive index determination all indicate a composition of approximately $Fa_{10}Fo_{90}$ for the olivine. No variation in composition from sample to sample, within a single sample, or within single grains was detected. Calculations based on the one published chemical analysis (Ross, Foster, and Myers, 1954, p. 707) give a composition of $Fa_{8.2}Fo_{91.8}$, which is very close to the value given by Davis and Hess (1949, p. 872).

Within the limits of accuracy of optical methods, the enstatite has a composition of approximately 90 percent of the magnesium silicate molecule, the same as the olivine. No chemical analysis is available. A lamellar structure is commonly seen in prismatic sections. These lamellae consist of very thin zones with a higher birefringence and consistent inclined extinction. At the margins of the Twin Sisters body, in grains partially serpentinized to bastite, the lamellae are unaffected by the alteration. This indicates a different composition for the lamellae and an origin by exsolution (see also Hess, 1960, p. 30).

Very small amounts of a bright green clinopyroxene occur as grains distributed along planar surfaces in the massive dunite. These planes have no relationship to other visible structures in the rock and do not mark any zone of actual rupture. These occurrences have suggested deposition in fractures to Thayer (in Ross, Foster, and Myers, 1954, p. 705). Chemically this clinopyroxene is a chromium diopside (Ross, Foster, and Myers, 1954, p. 709).

Chromite is ubiquitous. Mostly it occurs as grains disseminated throughout all rock types, less often as elongate schlieren, and rarely as chromitite masses. Throughout the entire Twin Sisters mass, chromite probably averages less than one percent of the total bulk of the rock. This chromite has also been analyzed chemically (Ross, Foster, and Myers, 1954, p. 710).

In addition to the chemical analyses noted above, samples of the Twin Sisters dunite have been analyzed for trace quantitites of Radium (Davis, 1947, p. 690; Davis and Hess, 1949, p. 861), of Potassium and Rubidium (Ahrens, Pinson, and Kearns, 1952), of Potassium (Holyk and Ahrens, 1953, p. 244), of Lithium, Scandium, Strontium, Barium, and Zirconium (Pinson, Ahrens, and Franck, 1953, p. 254), of Uranium, Thorium, and Lead (Tilton and others, 1956, p. 100), and of Uranium and Barium (Hamaguchi, Reed, and Turkevich, 1957,. p. 342, 344). The earlier isotopic composition data for lead must now, however, be disregarded (Tilton and Reed, 1960).

Early Textures

The earliest recognizable textural elements consist of rather coarse, anhedral, uneven-grained olivine crystals with irregular and often interlocking boundaries. Some enstatite grains occupy intergranular positions between the olivine grains, forming thin irregular zones partially surrounding individual olivines. Elsewhere very large enstatite crystals, up to one centimeter long, with a subhedral tendency, occur among anhedral olivine grains. Most of the enstatite contains the lamellae of clinopyroxene that are thought to indicate slow cooling and exsolution following deepseated crystallization (Hess and Phillips, 1938). Disseminated euhedral to subhedral chromite is common in the dunite. These textures may be the result of deep seated primary crystallization of the dunite minerals or may be due to an early stage in their metamorphic recrystallization. Critical evidence is lacking. In light of the subsequent history and resulting structures and textures, the latter possibility seems more likely.

Secondary Textures

Superimposed on the earlier textures are a series of deformational textures. The interpretation of these is critical to the understanding of the history of the dunite, including its mode of emplacement. The term "protoclastic" is frequently used to describe some of these textures. This term is generally understood to imply a magmatic origin and refers to granulation and deformation of mineral grains during a late state of intrusive motion of an igneous body. As will be shown below, the structures described here can be best understood in terms of the deformation of a solid mass quite analogous to similar structures found in other cataclastically deformed crystalline rocks. The term "cataclastic" is therefore preferred.

Three types of cataclasis are present: (1) granulation and bending of grains, (2) translation glide banding in olivine grains, and (3) cataclasis accompanied or followed by recrystallization.

Granulation and bending.—Almost every section of Twin Sisters dunite (as well as most other dunites (Williams, Turner, and Gilbert, 1954, p. 78)) displays some granulation. These areas generally consist of narrow zones of finely comminuted olivine, frequently containing olivine porphyroclasts, part of which may be elongate parallel to the granulated zone. With increasing deformation mylonites are produced. These cataclastic areas invariably contain the whole range of granulation products from submicroscopic up to fragments as large as five millimeters in diameter. In detail, the cataclastic zones vary considerably. Some are much finer grained than others. Some have relatively sharp margins whereas others have borders where granulation dies out more gradually. Some clearly represent considerable differential movement, and others show only very slight shearing.

Bending of mineral fragments is common in these shear zones, but it occurs throughout the rock to a somewhat lesser degree. In or adjacent to the granulated area, bending of olivine is shown by irregularly curved undulatory extinction, by trains of slightly separated fragments following the curve of bending, and in a few cases by deformed cleavage. Clearly olivine is able to yield by bending only to a rather small extent before fracturing. The best examples of bending are exhibited by enstatite grains. In some prismatic sections the cleavage is seen to be strongly curved with no sign of rupture. A similar contrast between the mechanical strength of olivine and enstatite has been observed by Tilley (1947) in the mylonites of St. Paul's Rocks.

Deformation bands.—Lamellae parallel or subparallel to (100) in olivine grains are abundant in many olivine-bearing rocks (Williams, Turner, and Gilbert, 1954, p. 78). These have been termed banded olivines by Hamilton (1957); his term is used here.

Banded olivine has been studied and variously interpreted by a number of workers. From recent experiments, Griggs, Turner and Heard (1960, p. 54) now attribute the

> "Development and strengthening of the undulatory bands to relative external rotation of subgrains in response to localized translation gliding upon some system or systems as yet unknown."

Ernst (1935) and Hamilton (1957) have interpreted the bands as indicating a separate deformational episode in the history of the olivine rocks followed by later inclusion and intrusion along with basalt. Brothers (1960), however, believes that the lamellae in olivine nodules and in occasional euhedral phenocrysts in some New Zealand lavas is the result of gravity deformation by the load of overlying crystallates in the magma chamber.

Banded olivine is very common in the Twin Sisters dunite; about 25 percent of the grains show some form of it, and no doubt many of the other grains are oriented so that it does not show. There are examples of all stages in the formation from incipient to sharply defined bands. In the early stages of development olivine grains display a poorly defined set of parallel zones of undulatory extinction. With increasing deformation the bands tend to become differentiated into definite alternating zones, each of which has a slightly different extinction from the adjacent bands. During the next stage the boundaries of the bands become more sharply defined until a straight fracture occurs between two adjacent bands. This rupturing has also been observed at Dun Mountain (Battey, 1960, p. 724). In some cases this straight fracture in one part of the grain becomes an irregular fracture in another part. Parts of the grain adjacent to these fractures, both straight and irregular, may show slight granulation. As the grain undergoing translation changes shape, gliding will proceed only as long as it is the easiest process of grain deformation. If adjacent grains, particularly large ones, are so located as to interfere with the changing shape, then either the deformation of that grain will cease, or another process of internal movement will be found. In a few grains the development of the irregular fracture from the simple straight one was clearly observed to be the result of interference by such an adjacent grain.

The development of sharply bounded extinction bands in olivine has indicated a process of polygonization to Griggs, Paterson, Heard, and Turner (1960, p. 24). The transition from sharply bounded to fractured bands with granulation observed in the Twin Sisters dunite suggests that the process is one of prolonged grain damage rather than recrystallization.

Recrystallization.—Mention of recrystallization features in olivine of deformed dunites was found in only two papers. Tilley (1947, p. 486), in his description of the dunite-mylonites of St. Paul's Rocks, noted small cross-cutting olivine veinlets indicating the regeneration of forsterite subsequent to the main mylonitization. Rothstein (1957, p. 13, 21) briefly mentions recrystallization textures in a peridotite of Eire and concludes that the consolidated mass was deformed while still hot. He only briefly mentions recrystallization and does not imply that it is a widespread or significant feature.

Throughout the Twin Sisters dunite mass, cataclastic textures identical with those already described have partially recrystallized. These recrystallized deformational structures modify earlier textures and are in turn often modified by later cataclasis without recrystallization.

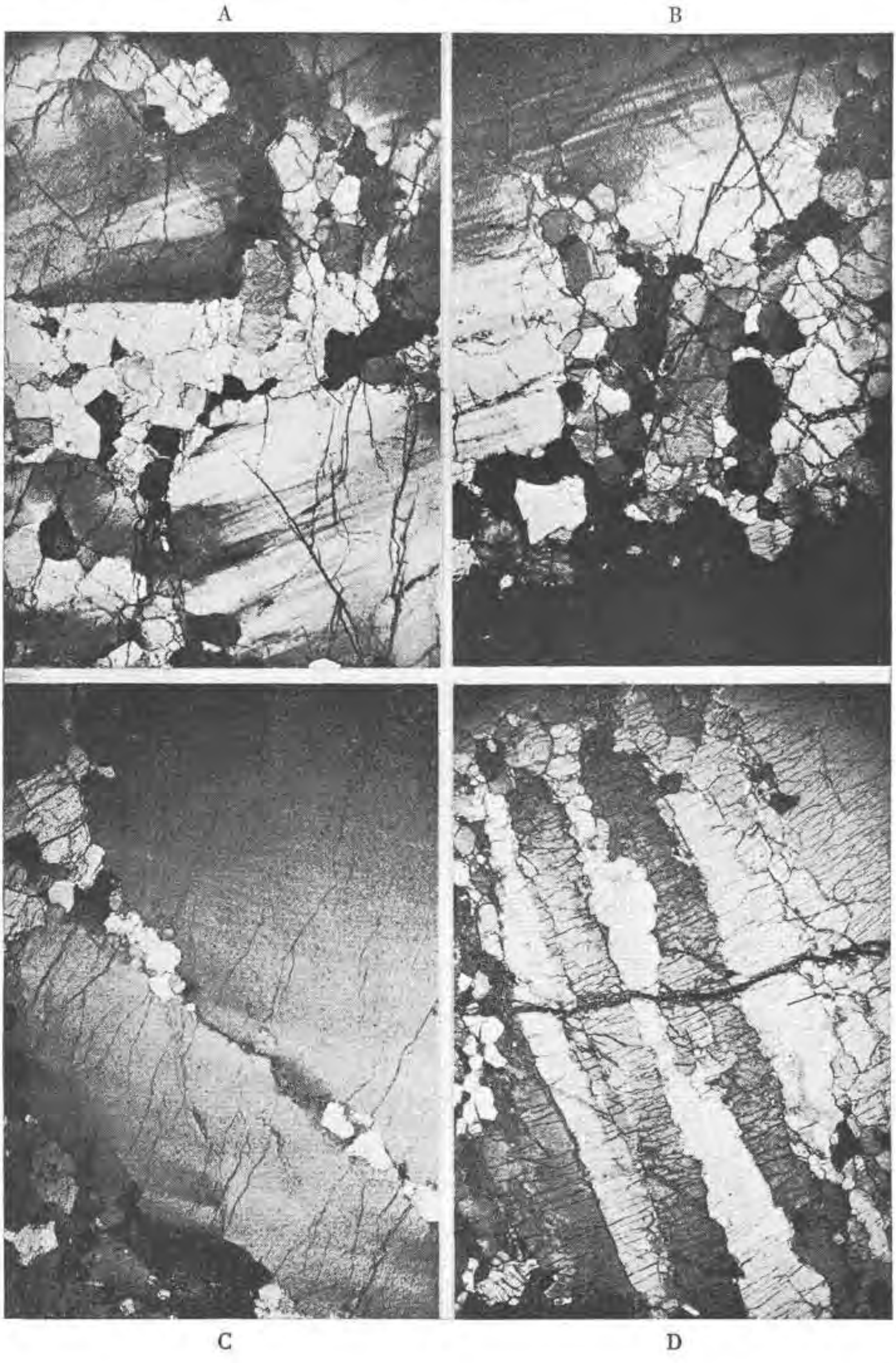
The most common recrystallization texture consists of fine-grained mosaic zones surrounding, embaying, and traversing large nonrecrystallized olivine grains which retain their earlier deformation features (pl. 1-A,B). These two distinct grain sizes were recognized by Thayer (in Ross, Foster, and Myers, 1954, p. 705) as "ragged green olivine grains up to five centimeters long, in a matrix of fine-grained olivine". Davis and Hess (1949, p. 872) also commented on similar textures. Apparently neither Thayer nor Davis and Hess recognized the recrystallization character. These zones are in every way analogous to the granulated and mylonitic areas produced by cataclasis, except they consist of a nearly equigranular mosaic of unstrained olivine grains instead of strained fragments of all sizes and degrees of comminution. These smaller, unstrained recrystallized grains surround and embay the large relicts. Those nearest the relicts have almost the same orientation as the original crystal; those more distant show considerable rotation. All the large nonrecrystallized grains retain the earlier undulatory extinction and translation bands. Proof that this texture is due to recrystallization of granulated material around porphyroclasts, and not to original porphyritic crystallization or to interprecipitate material, is conclusive where a thin unstrained mosaic zone cuts a single strained crystal (pl. 1-C).

Another distinctly different but equally conclusive recrystallization feature consists of broad bands with irregular sutured boundaries (pl. 1-D). That these are actually translation bands modified by partial recrystallization is shown by the following facts:

(1) The bands are still subparallel to (100), and each has only a slightly different extinction position from its neighbor.

(2) Nonrecrystallized bands within the subindividuals are subparallel to the recrystallized boundaries.

(3) Some bands show only very incomplete recrystallization. Nonrecrystallized portions of the bands are bordered by straight fractures identical with those described above.


A
B
C
D

The recrystallization of the bands into these sutured patterns is probably confined to places where deformation of the single grain reached the stage of fracturing. This is suggested by the preserved remnants of straight fractures, by the nonrecrystallized unfractured bands within the subindividuals, and by the presence of small, slightly rotated grains along the more irregular parts of some recrystallized boundaries.

Serpentine and Serpentinites

Serpentinites and incompletely serpentinized dunites are associated with both the Twin Sisters and the larger of the other two bodies. None was found in the third because of the alluvial and vegetative cover. The serpentinites are marginal to and transitional with the unaltered dunite. An accurate determination of the dimensions of this marginal zone is difficult. The serpentinite is less resistant to weathering and erosion than the dunite and is usually poorly exposed. A width of two to three hundred yards is the best estimate, based on an exposure on the southeast side of the Range in the vicinity of the "Big Slide" where landsliding has removed much of the cover. This same area offers the greatest variety of serpentinized rock types. Most of the petrographic details and conclusions are based on samples taken here. Additional data are supplied by specimens collected elsewhere along the margins of the Twin Sisters and from the serpentinized part of the other mass.

As the margin is approached from the dunite core, a rapid transition from unaltered dunite to massive serpentinite is observed. In thin section the serpentinite is seen to form a mesh-structure of antigorite and subordinate chrysotile in fractures in the olivine grains. The transition from olivine, first to olivine with antigorite along subrectangular cracks, and then entirely to serpentinite with mesh-structure is well shown in a number of sections. There is little doubt that this mesh-structure is good evidence of the identity of the original mineral. The typical massive serpentinite of the inner part of the marginal zone displays a fully developed mesh-structure of antigorite surrounding polygonal areas of light green serpophite. Veinlets of chrysotile and "iddingsite", containing irregular small opaque grains, are common.

To the outside of the massive serpentinite zone the rocks become slickensided and then are succeeded by highly foliated serpentinites at the contact. In moderately slickensided and foliated rocks mesh-structure and shredded antigorite are both present. Highly foliated varieties are rarely seen. In the "Big Slide" area, nearest the contact, such a rock is exposed; here it is weathered to a bouldery claylike material. The claylike substance consists of soft, grayish plates, which show all the folds and crenulations of typical schistose serpentinite. The boulders are crude, lens-shaped fragments of massive serpentinite

PLATE 1

Photomicrographs showing deformed and partially recrystallized olivine. The scale of each picture is the same; the long dimension is 5 mm.

A. Two strained porphyroclasts (upper left and lower right) surrounded by a mosaic zone of unstrained olivine grains.

B. Mosaic zone surrounding and embaying a large strained porphyroclast.

C. Thin unstrained mosaic zone and isolated unstrained grains cutting a single, large strained olivine crystal.

D. Translation bands with sutured boundaries.

bounded by slickensides. This suggests that the rarity of the foliated types is only apparent and actually represents paucity of exposures due to low resistance to weathering.

Only traces of serpentine are present in the interior portions of the masses. Where serpentine is found in the core, it is almost universally associated with prominant fracture zones as replacements of only the finest granulation products, or as a thin coating on some joint surfaces. Generally this internal serpentine shows no signs of shearing, although some of the joint coatings do show a slight development of slickensides.

Contacts

Like many other peridotite masses, the Twin Sisters dunite shows little or no contact metamorphic effect on the wall rocks. Most often this is explained by assuming a low-temperature intrusive mass. Low temperatures are independently established by a study of the serpentinization and internal structure as discussed below.

The emplacement of large intrusive masses into relatively shallow parts of the crust can reasonably be expected to have a profound structural effect on the country rock, and in many, though by no means all, intrusions, such an effect can be demonstrated. The Twin Sisters dunite, however, has not demonstrably displaced its wall rocks. In the surrounding country rocks, both the phyllite on the west and the sedimentary rocks on the east, no deviations from the regional structural trend could be discerned around the dunite mass. In other words, if the outcrop area of the dunite were covered, its presence could not be inferred from the structures known in the surrounding country rocks.

Certain structural elements associated with the contacts shed some light on the intrusive process. At five widely separated localities "exotic" blocks are trapped between the dunite and the country rock or enclosed in the marginal serpentinites. Lithologically these blocks are: (1) highly cataclastic pyroxenites, (2) cataclastic granitic gneisses, and (3) slightly altered volcanic rocks. It suffices to say that the pyroxenites are similar to those in other tectonic occurrences in the surrounding area, the metamorphic rocks are probably related to the pre-Carboniferous and pre-Cascade metamorphic "basement" crystalline rocks (Misch, 1960) found in Klippen both to the north and the south, and the volcanic rock probably is part of the upper Paleozoic Chilliwack group.

Age of the Peridotites

Lithologic, structural, and geographic features of the Twin Sisters and the two other smaller dunites strongly indicate a common period of intrusion. As they are not all intrusive into the same formations (they are found in contact with rock units of early Tertiary age and older), separate episodes of intrusion along the post orogenic fault cannot be excluded.

Peridotite intrusions are similarly scattered throughout presumably equivalent units elsewhere in this general belt. Misch (1952), Vance (1957, The geology of the Sauk River area in the Northern Cascades of Washington, unpublished Ph.D. thesis, University of Washington), Bennett and Thorsen (1960), Mills (1960), and the present work all have shown post-early Tertiary intrusion in widely separated areas along this belt. The strong lithologic similarities of these and other peridotites found in the older units suggests the possibility that, in addition to demonstrably older peridotites, some other post-early Tertiary masses may also be present.

Hess' view is that peridotite intrusions date the orogeny and he gives a small scale map (1955, p. 396) showing a line of Triassic ultrabasic intrusions which probably includes the Twin Sisters body. Similarly, Noble and Taylor (1960), from work in Southeastern Alaska, give a correlation map of ultramafic bodies including the some of the Northern Cascade masses that they date as early Cretaceous (and includes some of the same occurrences that Hess gives as late Triassic). It is, therefore, important to emphasize the Tertiary age of intrusion of some of these rocks.

Older peridotites are certainly known in the Cascades. Misch (personal communication) has found them east of the belt here discussed, where many occurrences are older than the Cascade (Skagit) metamorphism. North of Mount Baker, as well as immediately north of the area here described, he found serpentinites associated with Cretaceous thrusts. Farther to the south, the relationship of the ultrabasic rocks of the Mount Stuart area and the Cretaceous orogeny is not known, but they are definitely pre-Swauk in age (Smith, 1904).

The correlations and map of Noble and Taylor (1960, p. 189, 192) indicate an obvious possibility not yet considered. Their inclusion of the Twin Sisters dunite in this correlation is, in part at least, based on the preliminary statement of the present study (Ragan, 1959) and they say (p. 192):

> "It may be that this mass was originally crystallized as a typical zoned ultramafic body [as in Southeastern Alaska] at depth and has since been intruded upward as a solid, dry dunite mass. Certainly it is likely that this body was originally intruded in the early Cretaceous at the same time as the other ultramafic rocks of the Coast Range orogenic belt."

There are several reasons for objecting to such an interpretation. The underlying assumption is that all ultramafic bodies in this belt, regardless of local relationships, were emplaced at one single time. For the Northern Cascades this is demonstrably not true. Pre-, syn- and postorogenic intrusions are known. The lithologic correlation of the Twin Sisters dunite with the complexly zoned, early Cretaceous masses of Alaska is also weak. The Twin Sisters body is many times larger than the largest peridotite core of the zoned complexes. Certain rock types that are prominant in the zoned bodies, including hornblende-bearing peridotites and gabbros, are totally lacking in the Twin Sisters. The suggested two-step intrusion with a pause lasting from early Cretaceous into the Tertiary at some intermediate depth is not compatible with the evidence of internal movement in the solid state while still hot enough to recrystallize, as described above and further discussed below.

SERPENTINIZATION

The marginal serpentinite belts that surround both the 36-square-mile and the one-square-mile dunite bodies have roughly the same dimensions. If anything, the serpentinization of the smaller body is somewhat more complete because of greater fracturing. In any case, the amount of serpentinization is essentially independent of the size of the masses.

As noted, where traces of serpentine occur in the interior portions of the Twin Sisters body, it is restricted to certain joints or to fractures that could allow small quantities of water to penetrate. In the fractures, the general lack of deformed serpentine and the very incomplete alteration indicate that internal serpentinization was a very late event.

Where postserpentinization movement of the peridotite did occur, deformed serpentinites developed. The degree of slickenside development and of shredding of the serpentine minerals is thought to be roughly proportional to the amount of movement. Depending on the exact nature of the reaction, the upper limit of serpentine stability is 400° or 500°C (Bowen and Tuttle, 1949, p. 452). At the contact where deformed serpentinites are present, intrusion took place at considerably less than 400° or 500°C, and the stronger the effect of movement the lower the probable temperature. How much lower the temperature was is not known, but the absence of observable contact metamorphic effect, even in susceptible argillaceous rocks, suggests that it was quite low. Conceivably, however, the flow of water from the country rock into the dunite may have considerably reduced the temperature at the actual contact.

From the approximate uniformity of the width of the serpentinite margin surrounding both the small and very large masses, from the transition inward from deformed serpentinite to unaltered dunite, and from the very late stage internal trace of serpentine minerals it is concluded the serpentinization started at the margin and proceeded inward, and the source of the serpentinizing fluid was the country rock.

INTRUSION OF THE DUNITE MASS

Physical State during Intrusion

As Bowen and Tuttle (1949) have shown, a liquid or semiliquid (mush) of pure dunite composition free of fluxing agents cannot exist below the melting point of olivine (about 1800°C for $Fa_{10}Fo_{90}$). In the Twin Sisters dunite cataclastic structures and textures show that internal movement took place after primary formation of the dunitic material. Furthermore, internal deformation was in progress when the dunite was hot enough for the cataclastically deformed olivine to recrystallize. This cataclasis accompanied by recrystallization is completely analogous to the same type of texture found in certain metamorphic rocks, and for the same reasons must have taken place in the solid state. The demonstration that serpentinization occurred only during the latest stage of movement of the dunite body, and the otherwise complete lack of serpentine minerals associated with recrystallized olivine demonstrates that the dunite had been and remained dry until the mass encountered water-bearing rocks, and that even during this late stage only a narrow marginal zone was serpentinized. The lack of serpentine, and therefore of water, associated with the described examples of partial recrystallization indicates that during movement at higher temperatures more complete recrystallization, as indicated by fabric properties and indirectly by anisotropy of compressional wave transmission (Birch, 1960, p. 1097) can also take place without water.

The minimum temperature, under the pressures existing at depth, that will permit the recrystallization of deformed forsterite in the absence of solvents is unknown. As far as pyroxene-free dunite is concerned, the upper limit is the melting point. In enstatite dunites this limit can be further lowered below the 1557°C incongruent melting point of enstatite. In prominent internal fractures that show no recrystallization, the finest granulation products are frequently preferentially serpentinized. This indicates that the lower temperature limit of forsterite recrystallization and the upper temperature of serpentinization probably do not overlap. If so, then the recrystallization does not take place below 400°C. Based only on petrographic relationships within the dunite, the recrystallization temperature of the olivine can only be determined to lie in the broad range between 400° and 1557°C.

As yet, no complete experiments, such as those of Buerger and Washken (1947) using anhydrite, fluorite and periclase, have been performed with forsterite. From experiments on olivine and calcite, Griggs, Paterson, Heard, and Turner (1960) and Griggs, Turner, and Heard (1960) show that the behavior of some minerals resembles the general pattern of behavior of metals under similar conditions. Therefore metallurgical data may also apply. It is known, for example, that cold-worked metal fabric becomes much more strongly modified by annealing recrystallization at temperatures about halfway between absolute zero and the melting point (Griggs, Paterson, Heard, and Turner, 1960, p. 24). If extended to pure forsterite, this suggests that at about 775°C recrystallization is capable of modifying cataclastic olivine. It is also known that the critical temperature for recrystallization decreases with decreasing strain rate (Griggs, Turner, and Heard, 1960, p. 40). Actual deformation experiments of forsterite showed no recrystallization at 800°C and 5 kilobars (Griggs, Turner, and Heard, 1960, p. 50-56), although perhaps the strain rate was too low for recrystallization to proceed at this temperature.

The cited examples of recrystallization in the Twin Sisters dunite are very incomplete; and probably occurred at or near the lower temperature limit of recrystallization. The time sequence, cataclasis with incomplete recrystallization followed by pure cataclasis, likewise seems to indicate that recrystallization was at its lower limit. Direct geologic evidence in the form of observations on the occurrence of olivine in high-grade metamorphic rocks (in the sillimanite zone of the standard Dalradian type of progressive metamorphism and in rocks of the granulite and eclogite facies) suggests that under these conditions olivine recrystallizes at temperatures below the estimated 775°C, possibly as low as 500°C.

Based on these relationships, it is tentatively concluded that the olivine in the Twin Sisters mass may have recrystallized at temperatures of 600° to 700°C, and possibly as low as 500°C.

Because of the postulated low recrystallization temperature of forsterite, and because of a lack of really widespread, severe mylonitization within the body, it seems possible that at least part of the recrystallization accompanied the intrusive rise. However, this recrystallization cannot yet be directly related to the upward movement. The work of Ernst (1935), and of others, on inclusions in basalt demonstrates that dunitic material from a deep source does bear the imprint of deformation. It is, therefore, also possible that the recrystallized deformational features found in the Twin Sisters are the result of process that acted at depth before the rise, and that only cataclasis without recrystallization occurred during the actual intrusion. It is expected that the petrofabric study now in progress will help answer this important question. In either case, the demonstration that dunite does move as a dry, plastic solid probably at fairly low temperatures does prove that completely solid intrusion is possible under the proper conditions.

These conclusions based on this study, including possible recrystallization during intrusion, are somewhat similar to those suggested by Bowen and Schairer. Primarily on the basis of physicochemical considerations they conclude that a special mode of intrusion was needed for uniform dunite bodies occurring independently of rocks such as gabbro or norite (Bowen and Schairer, 1935, p. 205). Later, in discussing this special mode of dunite intrusion, which they visualize as occurring along zones of weakness, they say (Bowen and Schairer, 1936, p. 395):

> ". . . the extension of the fissure and its filling were nearly analogous to the slow growth of a volcanic spine, though in detail the mechanism would be very different from those involved in the flow of the extremely viscous liquid of a spine. The deformation of the crystalline mass would take place as a result of recrystallization, facilitated by the presence of a liquid of complex composition. The intensive forces involved render possible in some examples the complete expressing of the associated liquid."

I interpret this statement to mean that the mobility of the dunite mass is maintained by the process of recrystallization that accompanies the deformation.

Concerning the physical state of the dunite in these independent intrusive dunite bodies and the complex liquid they contain, they state (Bowen and Schairer, 1936, p. 395):

> ". . . [that] at the time of their intrusion they were crystalline or largely crystalline but that there was associated with them a complex liquid, either enveloping the mass as a whole or occupying crystal interstices, or both, and that this liquid was eventually forced upward into fissures or portions of the same fissure."

Near the final state of cooling, the liquid is assumed to be forced outward, and in its absence continued movement to be recorded as cataclasis without recrystallization.

Dunite Emplacement

When viewed in terms of the transfer of a large mass of dunite material from great depth to the present position, the above discussion describes only the physical condition of the crystalline mass either during or before the rise. Considering the mass as a whole, the intrusion of the dunite clearly involves the movement of material upward through overlying rocks. As it has been shown that the dunite was solid during much and probably all of its rise, the process must be forceful intrusion. There can certainly be no doubt that the location of the three dunite bodies on the presumed Sutter Mountain fault is the result of intrusion upward along this zone of weakness. The contacts between the solid dunite and the country rock are, then, essentially intrusive faults, and the included blocks of "exotic" rock types derived from depth help to confirm the faulted nature of this contact.

The position of the Twin Sisters body along the fault and the undeflected structures in its wall rocks suggests that the mass up-faulted its roof in attaining its present position, acting like a piston. At some point in the forceful upward movement of the solid mass along the fault zone, the force that produced this movement would have overcome the friction and exceeded the pressure exerted by the weight of the overlying rocks. At this point it would require less energy to block out the roof by faults and push both dunite and roof upward. This roof has since been removed by erosion.

When the dunite mass encountered water-bearing rocks, even if temperatures still were above those at which serpentinization can occur, friction was no doubt lessened. However, when reduced temperatures allowed the serpentine reaction to proceed and marginal serpentinites were formed, friction between the dunite and the country rock was considerably reduced (see Hess, 1955, p. 402). When this occurred, movement took place either largely or wholly at the margins producing the strongly schistose serpentinites typical of the contacts. The amount of internal deformation probably dropped to a minimum when contact friction was reduced in this manner. This is shown by the small amounts of unsheared serpentine minerals (clearly postmovement) in some of the large fractures in the internal parts of the mass.

The role of the marginal serpentinite in facilitating the upward movement is somewhat comparable to that of the enveloping "complex liquid" envisaged by Bowen and Schairer (1936). Both would tend to lubricate the intrusive fault zone. The processes are, of course, entirely different. The serpentinite owes its existence to the reaction of dunite with water from the country rock. For the Twin Sisters dunite the concept of Bowen's hypothetical magmatic "complex liquid" is replaced by the process of marginal serpentinization, at least as far as the latest stage of upward movement of the body is concerned. As far as the earlier stages are concerned, no envelope, either "complex liquid" or of serpentinite, appears to have been in existence.

THE TWIN SISTERS DUNITE AS AN ALPINE-TYPE PERIDOTITE

If the Twin Sisters dunite is compared with other peridotites, and its classification attempted, then it certainly is of alpine type. It has the following usual characteristics:

(1) There is broad concordance between the direction of elongation of the Twin Sisters body and the trend of bedding or foliation of the enclosed rocks.

(2) The Twin Sisters dunite and the two smaller masses, together with some other Northern Cascade peridotites, tend to occur in a linear belt.

(3) The Twin Sisters mass is associated with geosynclinal rocks, including graywackes, volcanics, and cherts.

(4) Its mineral composition is dominantly forsterite, accompanied by enstatite, chromium diopside, and chromite.

(5) Contact metamorphism is absent.

The one feature not usually associated with alpine-type peridotites is its date of intrusion with regard to orogeny and regional metamorphism (see Turner and Verhoogen, 1960, p. 310). In the Northern Cascades there are peridotites (serpentinites) that were intruded at the time of the Cretaceous orogeny and are thus of truly alpine-type. The Twin Sisters dunite mass, however, was intruded later than the main orogeny. This raises an interesting question concerning the date of intrusion of peridotites in other orogenic belts. That some, perhaps even most, were intruded at the time of orogeny is undoubted. The Twin Sisters body and the belt of Tertiary peridotites suggests the possibility that some of the masses in other belts, formerly lumped with the orogenic peridotites, may also have been intruded late in the orogenic cycle.

THE SOURCE OF DUNITIC MATERIAL

Reasons for favoring a derivation of alpine-type peridotites from the upper mantle have been fully discussed by an number of recent workers. Reviews by Turner and Verhoogen (1960, p. 307-316, 434-436) and by de Roever (1960, 1961) include the following two main points:

(1) There is a remarkable compositional similarity between the widely occurring peridotite inclusions in basalts and alpine peridotite bodies.

(2) These inclusions and the peridotite masses are characterized by deformational features.

As shown, the Twin Sisters dunite joins this group for the same reasons. The conclusion based on this study is that solid, dry dunite is capable of intrusive movement. The demonstration of a mechanism of such intrusion lends considerable weight to the hypothesis of de Roever (1957, especially p. 144-145) that perhaps alpine-type peridotite masses in general are tectonically transported blocks derived from the peridotite shell.

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