

neled and non-channeled, were probably of major importance in the development of the flat interchannel areas and the deep-sea fans.

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## The Darling Lake Mafic and Ultramafic Pluton, Washington: Petrology, Gravity and Structure

The Darling Lake pluton is here named for a small moraine-dammed pond  $3\frac{1}{2}$  miles west-northwest of Okanogan, Washington. The pluton crops out in the rolling hills north of the lake and seemed worthy of further study when examined in reconnaissance by Menzer (1964). Subsequently, Taylor conducted detailed field and petrographic analyses, Swanberg studied the gravity of the area and Menzer looked more closely at the contact metamorphism and structure of the country rocks. This note is concerned with some of the results of these investigations.

Our work has been supported under a Research Corporation grant to Menzer for studies in the Okanogan Range and by Southern Methodist University. For this we are indeed grateful.

#### Geological Setting and Structure

The Darling Lake pluton is one of a number of small mafic to ultramafic intrusions in the Okanogan Range in north-central Washington. It comprises an olivine-bearing suite of anorthositic gabbro, gabbro, norite and peridotite which intruded sillimanite-almandine-amphibolite facies schist and gneiss subsequent to regional metamorphism. The latter has been bracketed as occurring sometime after the Noric and before  $129 \pm 1.8$  m.y. ago; that is, between late Triassic and early Cretaceous (Menzer, 1970).

Contact metamorphism of these high grade schists and gneisses is quite local and varied in intensity. In general, quartzo-feldspathic rocks were insensitive to the heat of intrusion while pelitic schists were the most susceptible. The well developed foliation of many pelitic schists was weakened when the phyllosilicates underwent static recrystallization in response to the intrusion. Mineral assemblages indicative of the sillimanite zone regional metamorphism had persisted through the contact metamorphic episode in most thin sections examined. However, pistacite and clinozoisite formed in some of these rocks,—an indication that their maximum temperature during recrystallization did not exceed that of the hornblende hornfels facies.

Structurally, the Darling Lake pluton is a small stock with 2000 feet of vertical exposure and a surface area slightly less than one square mile. Salients of schist and gneiss project into the stock from the north and the south; hence, the outer contact of the pluton is somewhat fiddle-shaped in detail. The metamorphic rocks in these prongs probably are quite thin as they were not evident in the gravity study. Because the foliation of xenoliths in the stock parallels the metamorphic structure of the country

rocks, these blocks are thought to be roof pendants. We believe that the contact around the prongs and the xenoliths represents part of the original roof of the pluton and that very little of this body has been eroded.

Although the country rocks are truncated along the northern and southern contacts of the stock, the schists and gneisses wrap around the western and eastern borders and much of the room required for intrusion may have been provided by dilation. Space also seems to have resulted from faulting on the east side.

#### Petrology

Medium to coarse-grained hypidiomorphic hornblende gabbro makes up approximately 95 percent of the outcrop area of the pluton, and ultramafic rocks constitute the remaining 5 percent. The gabbro has an estimated average mode of 45 percent labradorite-bytownite, 10 percent diopsidic augite, 10 percent enstatite-bronzite, 10 percent colorless magnesium-rich hornblende, 20 percent actinolite-tremolite, and small amounts of clinzoisite, biotite, chlorite and apatite. The lack of iron-rich phases and the large amount of deuteric alteration is responsible for the unusually light color of the gabbro. A partial chemical analysis of a typical gabbroic sample is given in Table I.

TABLE I. Partial chemical analyses of a typical gabbroic sample.

SiO <sub>2</sub>	51.00
TiO <sub>2</sub>	0.48
Al <sub>2</sub> O <sub>3</sub>	16.89
CaO	10.02
FeO	6.74
K <sub>2</sub> O	0.56
MgO	8.32
MnO	0.16
Na <sub>2</sub> O	1.80
	95.97

Analyzed by atomic absorption photospectrometry by J. A. Jones, 1969. Total iron reported as FeO.

The ultramafic rocks occur as irregular pods of varying dimensions which are restricted to the interior of the pluton. These rocks are medium- to coarse-grained and dominantly allotropic, and may best be described as hornblende-plagioclase peridotites. Primary mineral phases, which occur in variable amounts, include olivine (For<sub>77.3</sub>, determined by the x-ray method of Hotz and Jackson, 1963), orthopyroxene (En<sub>87.88</sub>, determined by the refractive index, Deer and others, 1962-1963), diopside, green spinel, magnesium-rich hornblende, calcic plagioclase, colorless phlogopite, and talc. Serpentine is almost totally absent, appearing only as veinlets cutting olivine. Secondary minerals such as actinolite-tremolite, iddingsite, calcite, and talc are present in varying amounts. Orthopyroxene, plagioclase, hornblende, and phlogopite crystallized in that order, and many grains are poikilitic. The primary minerals hornblende and phlogopite indicate a high P<sub>H<sub>2</sub>O</sub> during the late stages of crystallization.

Contacts between gabbro and ultramafic rocks are gradational and demonstrate compositional variations ranging from peridotite to gabbro. Chilled margins are completely absent, and the mineralogy of the contacts suggests mechanical mixing of the two rock types while in a relatively fluid state. Thus, the mineralogy and contact relations suggest a genetic relationship between the peridotite and the gabbro. Irvine (1967) thinks ultramafic rocks that are differentiated from gabbroic magma may be expected

to contain interstitial plagioclase as a product of the interprecipitate magma. The Darling Lake rocks satisfy this criterion.

The Darling Lake pluton can be best classified within the ultrabasic rock association outlined by Wyllie (1967) as "Minor associates of batholithic complexes." This association is described by Wyllie as ultramafic members which usually are concentrated within the stocks that, in turn, form satellites to major batholithic complexes. Joplin (1959) discusses many occurrences of mafic bodies associated with large batholithic complexes in which ultramafic rocks occur as large blocks within small mafic stocks. In most of the cases discussed by Joplin, the mafic intrusives were determined to be the earliest magmatic phase. The time of intrusion of the Darling Lake gabbro cannot be properly placed into the sequence of post orogenic intrusions in the area due to lack of mutual contact: the Darling Lake pluton is completely enclosed by metamorphic rocks. Local spreading of the schists and gneisses near the contact to make room for the intrusive magma; the lack of inclusions of country rock, which may represent either a lack of brecciation associated with stopping or the ease with which xenoliths are incorporated in the magma; and the lack of a significant contact aureole are factors indicating that the country rock may have been hot and pliable during the emplacement of the pluton.

The Darling Lake ultramafic mineral assemblages closely match the vapor-deficient amphibole-bearing mineral facies consisting of the equilibrium assemblage forsterite + diopside + enstatite + anorthite + amphibole which is stable only under conditions of total pressure of less than 6.9 kilobars (O'Hare, 1967). In addition, Yoder and Tille (1962) suggest that hornblende crystallizes after plagioclase in a basaltic magma only at P<sub>H<sub>2</sub>O</sub> below 3 kilobars. In a study of the stability of phlogopite, Yoder and Eugst (1954) show that phlogopite is stable only at pressures greater than 2.4 kilobars in mafic rocks. These data suggest a P<sub>H<sub>2</sub>O</sub> between 2.4 and 3.0 kilobars during the late stages of crystallization and a P-total greater than P<sub>H<sub>2</sub>O</sub> but less than 6.9 kilobars. The peridotite and gabbro crystallized together, as the textural and mineralogical evidence indeed suggests, these pressure conditions may also apply to crystallization of the gabbro.

#### Gravity

A total of 250 gravity stations were occupied in a rectangular area approximately 20 miles long and 15 miles wide for the purpose of supplementing geologic data of the Darling Lake pluton. In the immediate area of the pluton stations were located at intervals of 500 feet along 3 profiles, each extending 2 miles on either side of the one mile long outcrop area. In the surrounding region, stations were located at approximately every mile. The relative accuracy of the gravity measurements is better than one milligal. Simple Bouguer and residual anomalies were obtained by conventional methods and outer zone terrain corrections were calculated for all stations. Inner zone corrections were calculated for several selected stations and found to have little effect on the relative anomaly.

In order to analyze the subsurface geometry, the pluton was assigned a number of 3-dimensional models whose dimensions and physical properties agreed with those observed in the field. The densities of the units were obtained by the method of measuring gravity over a hill (Nettleton, 1940). This method has the advantage that it samples a large amount of material and it is unaffected by weathering on the surface. The measured densities are given in Table II. The outcrop area is roughly circular with

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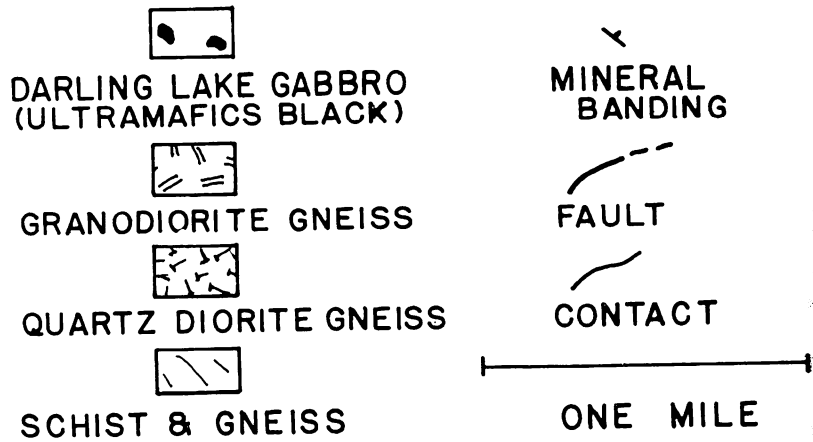
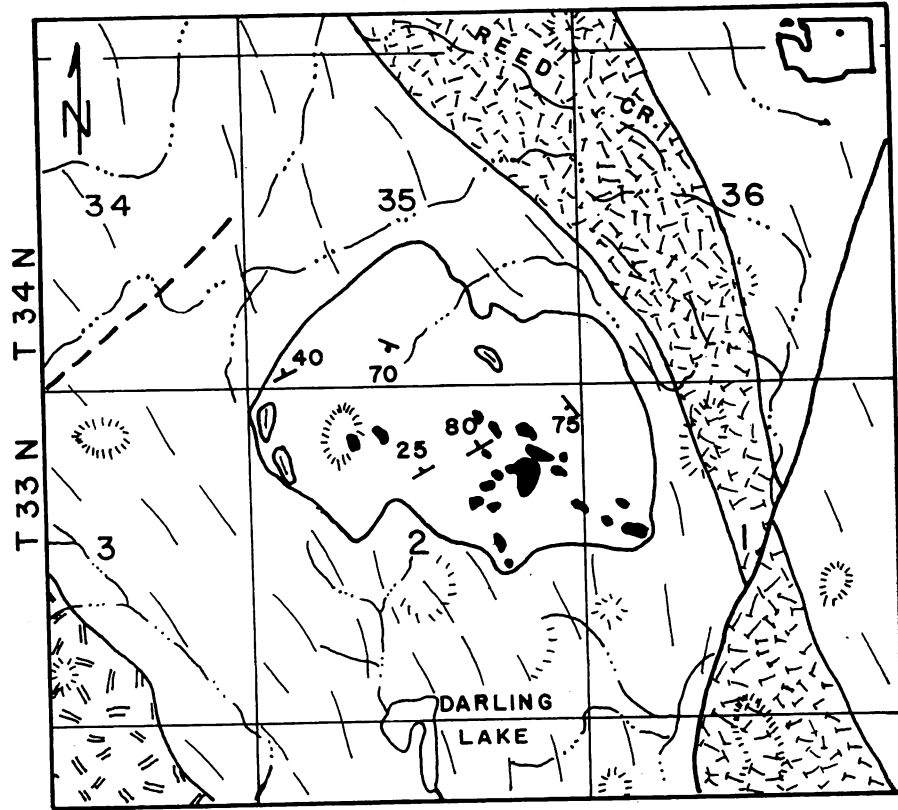


Figure 1. Geologic map and index map of Darling Lake area, Washington.

TABLE II. Rock densities determined in the gravity study.

Schist and gneiss unit	2.88-2.92 gcm <sup>-3</sup>
Quartz diorite gneiss unit	2.72-2.82 gcm <sup>-3</sup>
Darling Lake unit	3.14-3.18 gcm <sup>-3</sup>

a major diameter of just over one mile. The surface area for the model was then chosen as a square with area equal to the observed outcrop area. A vertical dip was assigned to the contact on one end of the model in order to agree with field exposures of over 2000 vertical feet along the cliff on the southeast side of the pluton. The dips in the plane of the residual profile were allowed to vary over all reasonable values, as was the depth to the bottom of the stock.

Theoretical gravity profiles for these models were then calculated by a computer technique discussed by Swanberg (1968) and compared with the observed profile. The sub-surface dimensions of the models were adjusted until the two profiles agreed.

Figure 2 shows a sampling of vertical cylinders, all of which produce an anomaly profile whose half width is less than the observed profile. These models show conclusively that the Darling Lake Pluton cannot be represented by a cylinder or an inverted frustum of a cone. Physically, this implies that the pluton must be large at depth than at the surface. If the original shape of the pluton could have been represented

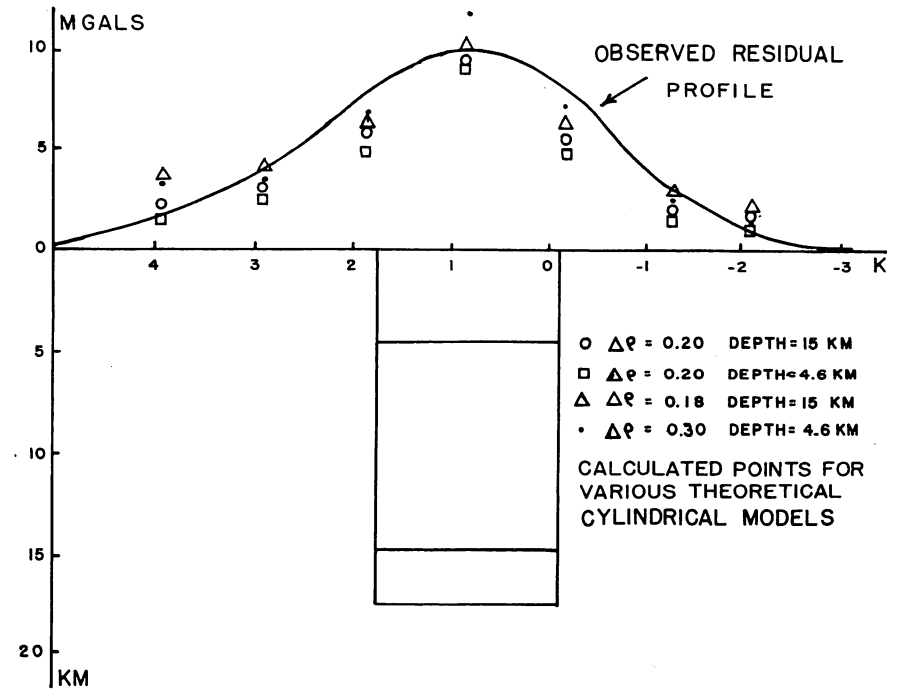


Figure 2. Comparison of calculated points for various theoretical cylindrical models with observed residual profile. See text for discussion.

resented by a truncated cone, a sphere or a "tear-drop," the present outcrop area would represent a horizon somewhere near the top of the original body, implying that little of the original body has been eroded.

Figure 3 shows the two most geologically reasonable models whose theoretical profiles are in close agreement with the observed profile. These models are not unique in that the dips, densities, and distance to the bottom of the model may be varied slightly without significantly affecting the gravity. The minimum distance to the bottom of the "flat bottom" model is 1500 meters, with outward dipping angle of 30°, whereas the maximum distance is 2100 meters with dipping angles of 74°. A median model with values of 1750 meters and 50° is illustrated in Figure 3.

A wide variety of "tear drop" models also can be made to fit the observed anomaly profile. A typical model with outward dips of 47° changing to inward dips of 65° at 1050 meters is shown in Figure 3.

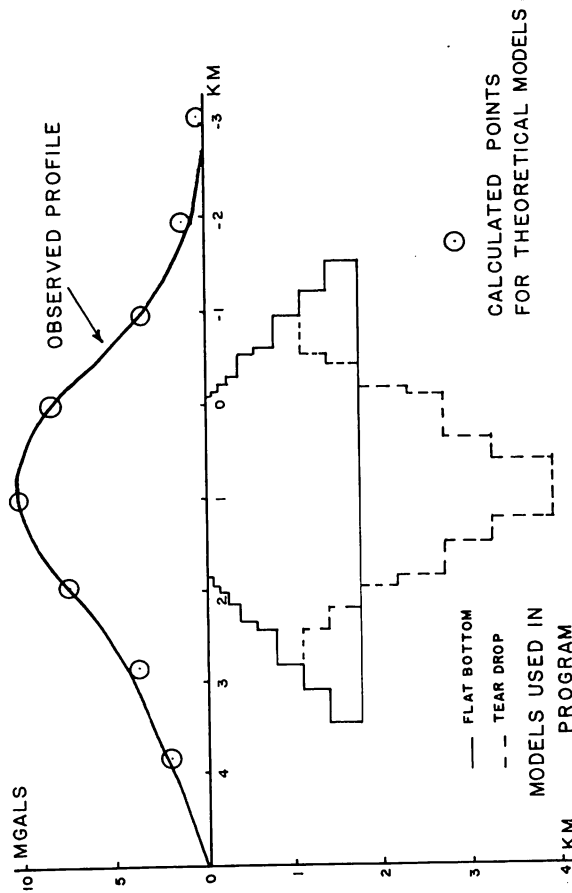


Figure 3. Comparison of calculated points for a theoretical flat bottom model and a theoretical tear drop shaped model with the observed residual profile. See text for discussion.

A wide variety of "tear drop" models also can be made to fit the observed anomaly profile. A typical model with outward dips of 47° changing to inward dips of 65° at 1050 meters is shown in Figure 3.

#### Summary

The Darling Lake pluton is a small stock of gabbro and related ultramafic rocks forcefully emplaced after a mid-Mesozoic episode of regional metamorphism. It probably has a teardrop shape and may represent an early mafic differentiate of the Cretaceous magmatic cycle in north-central Washington.

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