

Geology of Part of the Nelchina River Gabbronorite and Associated Rocks, South-Central Alaska

By Laurel E. Burns

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GEOLOGY OF PART OF THE NELCHINA RIVER GABBRONORITE AND ASSOCIATED ROCKS, SOUTH- CENTRAL ALASKA

By Laurel E. Burns¹

ABSTRACT

The Nelchina River Gabbronorite forms the largest mass in a discontinuous elongate zone of fault-bounded bodies composed dominantly of mafic and ultramafic plutonic rocks in south-central Alaska. The mafic and ultramafic rocks within this zone have been interpreted to be the fractional-crystallization products of a hydrous basaltic magma that produced basaltic and andesitic volcanic rocks. Minor quartz diorite, tonalite, granodiorite, and metasedimentary and metavolcanic rocks are intrusively and tectonically mixed with the mafic and ultramafic rocks and form an integral part of the Nelchina River Gabbronorite. The relationship of these subordinate rocks to the gabbroic rocks has not been clearly understood by previous workers. Detailed geologic mapping, petrographic study, and geochemical analysis along a glacially polished strip of rocks—the Nelchina transect—leads to the following observations and conclusions of relevance to the origins of island-arc plutonic rocks. (1) Some of the gabbroic layering formed by in situ crystallization, whereas other layering formed by multiple injection of gabbroic magma effectively producing a coarse-grained sheeted-dike (or sill) complex. (2) Although the dike complex displays features generally attributed to classic layered sequences—such as size-graded layers, phase contacts, and wispy layering—the field relationships observed in the Nelchina transect indicate that these features formed as a result of multiple intrusion and flow foliation. (3) Textures of the metasedimentary and metavolcanic rocks that are intruded by the gabbroic rocks are typical of those produced by deep-seated (catazonal) intrusions. This observation indicates crystallization at pressures of at least

3 to 10 kbar (300-1,000 mPa), or about 10 to 30 km depth—on the basis of mineral compositions of the Nelchina River Gabbronorite and the nearby, related Tonsina ultramafic-mafic assemblage. (4) Plastic-deformation textures in both the gabbroic rocks and the quartz diorite-tonalite suggest that quartz diorite and tonalite magmas intruded while the gabbroic rocks were still warm though probably after most of the gabbroic intrusions were emplaced. The plastic-deformation textures significantly constrain both the assigned age of the gabbroic rocks and interpretation of processes of formation of arc complexes in general.

INTRODUCTION

The Nelchina River Gabbronorite (described and formally named herein) consists dominantly of gabbronorite (two-pyroxene gabbro) of Early to Middle Jurassic age with minor ultramafic rocks, quartz diorite, tonalite, granodiorite, and metasedimentary and metavolcanic rocks. The Nelchina River Gabbronorite (equivalent to the Nelchina Complex of Burns, 1985) forms the largest mass (170 km long by 2-10 km wide) in a discontinuous elongate zone of fault-bounded bodies, composed dominantly of mafic and ultramafic plutonic rocks and known as the Border Ranges ultramafic and mafic complex (Burns, 1985), which crops out discontinuously from Kodiak Island to near Tonsina. These rocks crop out in the southern part of the Peninsular terrane in south-central Alaska (fig. 1). Field relationships, petrologic and compositional data, and geochronology suggest that these mafic-ultramafic rocks, including the Nelchina River Gabbronorite, are part of the plutonic core of an intraoceanic island arc of Early to Middle Jurassic age and its associated metamorphic rocks (Burns, 1985). The mafic-ultramafic rocks appear to be genetically related to the andesitic volcanic rocks that crop out farther north and probably represent the fractional crystallization product associated with these andesitic volcanic rocks (Burns, 1985; Newberry and others, 1986).

¹Present address: Alaska Division of Geological and Geophysical Surveys, 794 University Ave., Suite 200, Fairbanks, Alaska 99709.

This report describes the geology of a 6-km by 0.3-km strip of glacially polished rocks of the Nelchena River Gabbonorite (figs. 1; locality C, fig. 2; pl. 1). The strip is located in the eastern part of the Anchorage (1:250,000) quadrangle along the west edges of secs. 29 and 32, T. 1 S., R. 10 W., and secs. 5 and 8, T. 2 S., R. 10 W., of the Anchorage C-1 (1:63,360) quadrangle. This strip is situated along the west side of the valley of the Nelchena River and adjacent to the lateral moraine. These nearly continuous exposures, referred to herein as the "Nelchena transect," effectively constitute a cross section through the northern Chugach Mountains. The transect, shown as the

three contiguous areas a, b, and c on plate 1, is herein designated as the type locality for the Nelchena River Gabbonorite. The glacially polished outcrops along the Nelchena transect reveal textures and contact relations that are invaluable for understanding the processes that formed the gabbonorite body.

PREVIOUS WORK

Geologic mapping of the Nelchena River Gabbonorite was largely of reconnaissance nature prior to the present

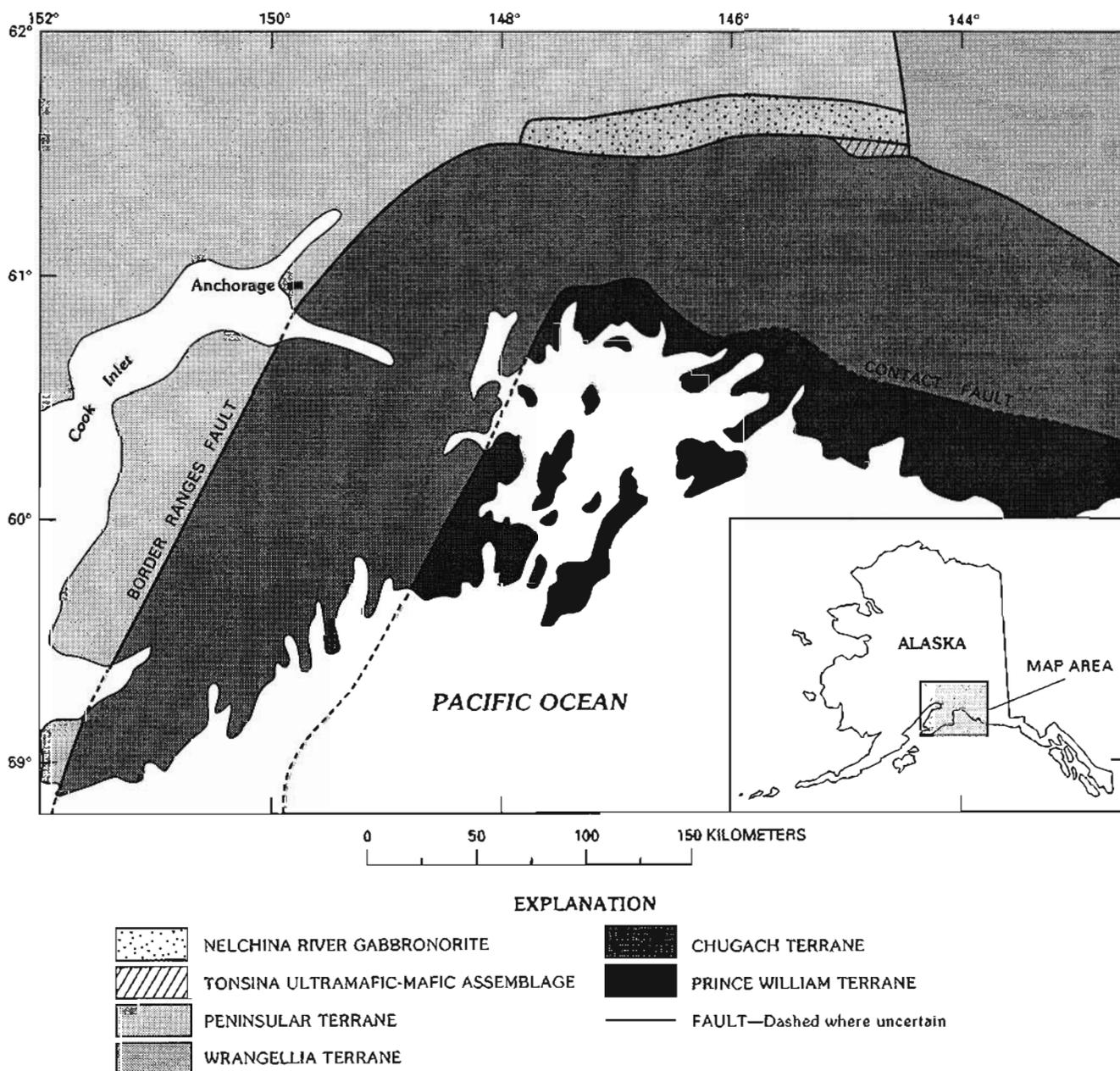


Figure 1. Generalized geologic map of part of south-central Alaska showing approximate location of the Nelchena River Gabbonorite and the Tonsina ultramafic-mafic assemblage. Modified from Plafker and others (1977).

study. During reconnaissance mapping, Grantz (1960; 1961a, b; 1965) and Andreason and others (1964) noted the existence of plutonic rocks of intermediate composition along with minor amounts of gabbroic rocks in the north-central Chugach Mountains.

The presence of a large body of mafic plutonic rocks in the Nelchina River area was not known until 1979-80 when Winkler and others (1981) and Pessel and others (1981) mapped portions of the body at scales of 1:250,000 and 1:63,360, respectively. Burns and others (1983) mapped the western part of the body in the northeastern Anchorage quadrangle at a scale of 1:25,000. Burns (1983) described aspects of the Nelchina River Gabbonorite not presented in this paper. Burns (1985) summarized and interpreted the geology of the mafic-ultramafic rocks along the northern Chugach Mountains.

Published aeromagnetic studies of the area include the 1:250,000-scale Valdez quadrangle (U.S. Geological Survey, 1979) and part of the northern part of the 1:250,000-scale Anchorage quadrangle (Alaska Division of Geological and Geophysical Surveys, 1973); aeromagnetic maps (1:250,000) with interpretations include those of Andreason and others (1964) and Case and others (1985). Gravity maps (1:250,000 and smaller scale) of this area were published by Andreason and others (1964), Barnes (1977), and Burns (1982). Burns (1982) also included both aeromagnetic and gravity modeling of the Nelchina River Gabbonorite.

PRESENT STUDY

The description of the type section of the Nelchina River Gabbonorite in this paper results from three summers of regional geologic mapping at 1:25,000 scale of the Nelchina River Gabbonorite (1979-80, 1982), including helicopter time to view and map different parts of the Border Ranges ultramafic and mafic complex, and one summer of detailed geologic mapping at 1:2400 scale of the Nelchina transect (1981). Twenty-six rocks were analyzed for major-oxide compositional data and about 300 thin sections from the Nelchina River Gabbonorite were examined petrographically to determine the petrology and mineralogy of the body.

ACKNOWLEDGMENTS

Three funding agencies supported the field and lab work that made the present study possible. The Alaska Division of Geological and Geophysical Surveys (ADGGS) provided support for the four summers of field geologic map-

ping (1979-82). Additional helicopter time was supplied by Gary Winkler of the U.S. Geological Survey (USGS) as part of the Alaska Mineral Resource Assessment Program (AMRAP) of the Anchorage and Valdez quadrangles. The major-element geochemical analyses of 26 rocks were performed by the ADGGS laboratory. About 300 thin sections were provided by the ADGGS and the USGS. Funding for microprobe analyses was provided by National Science Foundation grants EAR80-01076 and EAR81-15522 through N.H. Sleep of Stanford University.

The criticisms of R.G. Coleman, J.G. Liou, R.J. Newberry, G.H. Pessel, J.E. Case, N.H. Sleep, R.R. Compton, N.J. Page, and A.B. Ford are gratefully acknowledged. A.C. Eddy provided excellent editorial comments. Assistance from S.M. Stone and J.R. Le Compte on nomenclature proved very helpful. G.H. Pessel, J.C. Pessel, and K.S. Emmel plane-tabled the topographic map of the area.

REGIONAL SETTING

The east-west trending Nelchina River Gabbonorite crops out along the north edge of the Chugach Mountains in the southern part of the Peninsular terrane (figs. 1, 2); it overlaps the northeastern part of the Anchorage quadrangle and the northern part of the Valdez quadrangle.

Although Quaternary alluvium largely covers the eastern half of the body, geologic mapping and aeromagnetic data indicate that gabbroic rocks are present from near Tonsina to the Matanuska Glacier, a total distance of 170 km (Pessel and others, 1981; Winkler and others, 1981; Burns, 1982; Burns and others, 1983). The western part of the Nelchina River Gabbonorite, from Tazlina Lake to the Matanuska Glacier, is well exposed. The body appears to be everywhere fault bounded; no intrusions of gabbroic rocks are present in surrounding rocks.

The Nelchina River Gabbonorite is herein named for the Nelchina River; its type locality is designated as the previously described Nelchina transect (see "Introduction"). The unit is composed dominantly of various types of gabbonorite with lesser quartz diorite, tonalite, granodiorite, and ultramafic, metasedimentary, and metavolcanic rocks. The gabbonorites and the quartz diorite, tonalite, and granodiorite intruding the gabbonorite are considered Early to Middle Jurassic in age (Winkler and others, 1981). The metavolcanic and metasedimentary rocks are clearly older than the plutonic rocks, but their protolith ages are uncertain. These metamorphic rocks show some similarity to the Pennsylvanian and Permian Skolai Group (MacKevett, 1976) to the east and the rocks of Early Jurassic metamorphic age described by Carden and Decker (1977) near the Eklutna Complex. Minor amounts of Cretaceous(?) trondhjemite and Tertiary felsite intrude the

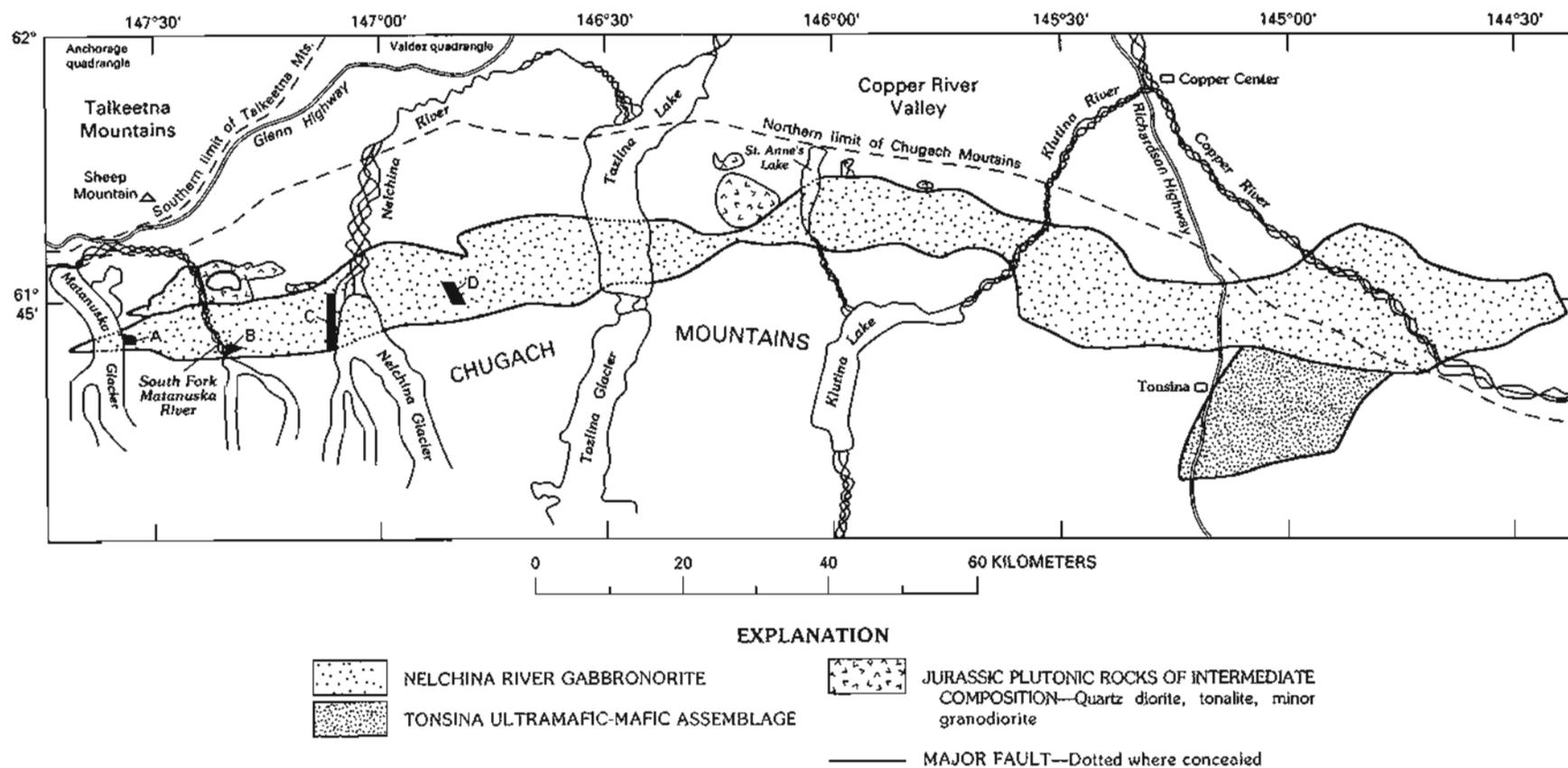


Figure 2. Detailed location map showing the Nelchina River Gabbro-norite, the Tonsina ultramafic-mafic assemblage, Jurassic plutonic rocks of intermediate composition, and major faults. *A*, Reference locality for dikes of quartz diorite and trondhjemite intruding gabbro-norite east of the Matanuska Glacier; *B*, reference locality for metasedimentary and metavolcanic rocks intruded by minor gabbroic rocks; *C*, Nelchina transect, type locality for the Nelchina River Gabbro-norite; and *D*, reference locality for the Barnette Creek section of cumulus-layered gabbro-norite. Modified from Winkler and others (1981), Pessel and others (1981), and Burns and others (1983).

Nelchina River Gabbonorite. The Nelchina River Gabbonorite is thus regarded as Jurassic in age.

A reference locality for the cumulus-layered gabbonorite of the Nelchina River Gabbonorite, a ridge where no quartz diorite or metasedimentary rocks are present (Burns, 1983), is situated east of Barnette Creek in the Valdez quadrangle (locality D, fig. 2). Within T. 1 S., R. 9 W. of the Valdez D-8 quadrangle (1:63,360), the ridge trends southeastward from the southeast corner of sec. 22 and continues through the corner of sec. 23 and across sec. 26. A reference locality for gabbroic rocks intruded by dikes of quartz diorite and trondhjemite is present east of the Matanuska Glacier in the Anchorage C-2 quadrangle (1:63,360) at the boundaries between secs. 25 and 36, T. 19 N., R. 10 E., and between secs. 30 and 31, T. 19 N., R. 11 E. The dike rocks crop out on both sides of an east-west-trending creek (locality A, fig. 2) and are shown as a distinct unit on the map by Burns and others (1983). A reference locality for the metamorphic rocks is also present in the Anchorage C-1 quadrangle (1:63,360) in the SE $\frac{1}{4}$ sec. 32, T. 19 N., R. 12 E. (locality B, fig. 2). This outcrop is a glacier-polished strip on the east side of the South Fork of the Matanuska River; these metamorphic rocks are shown as a distinct map unit by Pessel and others (1981).

On the north, the Nelchina River Gabbonorite is fault bounded against quartz diorite, tonalite, and minor granodiorite of Jurassic age and against andesitic volcanic rocks of the Lower Jurassic Talkeetna Formation (Pessel and others, 1981; Winkler and others, 1981; Burns and others, 1983). Barker and Grantz (1982) concluded that the Talkeetna Formation represents the volcanic part of an intraoceanic island arc on the basis of major-oxide and trace-element compositional data. The quartz diorite and tonalite intrude the Talkeetna Formation as well as the gabbonorite of the Nelchina River Gabbonorite.

To the south, the Nelchina River Gabbonorite is generally fault bounded against the McHugh Complex by a Tertiary high-angle fault. The McHugh Complex is a subduction complex with an accretion age of mid(?) Cretaceous and a protolith age of Jurassic and Cretaceous (Plafker and others, 1985). The McHugh Complex in this area is a chaotic mixture of massive greenstone, chert, pillow basalt, graywacke, and argillite (Winkler and others, 1981). Some of the Tertiary high-angle faulting has locally placed the Valdez Group (a Late Cretaceous accretionary wedge) against the south margin of the Nelchina River Gabbonorite (Pessel and others, 1981; Burns and others, 1983). The Valdez Group consists primarily of metasediment, metasilstone, and argillite (Clark, 1972).

The easternmost part of the Nelchina River Gabbonorite is faulted against the Wrangellia terrane of Jones and others (1981) (Winkler and others, 1981); the westernmost part pinches out between two crosscutting high-angle Tertiary faults (Burns and others, 1983).

GABBRONORITE OF THE NELCHINA RIVER GABBRONORITE

AGE AND COMPOSITION

The Nelchina River Gabbonorite includes layered and massive gabbonorite, magnetite gabbonorite (with greater than 5 percent primary iron-titanium oxide), and leucogabbonorite (with 65-90 percent calcic plagioclase). (Lithologic terminology is that of Streckeisen (1976) with the exception that pyroxene-hornblende gabbonorite is herein called hornblende gabbonorite.) No further distinction is made between gabbonorite and magnetite gabbonorite in this report because of highly variable amounts of magnetite over small areas. Anorthosite, hornblende gabbonorite, and leuconorite are also present; gabbro and olivine-bearing gabbro are extremely rare. Serpentinized ultramafic rocks, generally wehrilite, troctolite, and chrome-bearing dunite, are volumetrically very minor but are present in discontinuous fault slices near the south edge of the Nelchina River Gabbonorite. Dikes and small plutons of quartz diorite, tonalite, and trondhjemite are abundant in the Nelchina River Gabbonorite but are commonly too small to depict on regional geologic maps (for example, Burns and others, 1983).

Potassium-argon dating of quartz diorites and related rocks in the north-central Chugach Mountains yields ages of 188 to 165 Ma (Winkler and others, 1981; Pavlis, 1982). These ages are about the same as potassium-argon ages on hornblende from the Nelchina River Gabbonorite and from a klippe of gabbroic rocks to the south (see Winkler and others, 1981). Five potassium-argon ages on hornblende and one on clinopyroxene from five gabbroic rock samples range from 188 to 154 Ma (Winkler and others, 1981). Only one of these five ages is younger than 166 Ma. Two older potassium-argon hornblende ages, 419 and 267 Ma (Winkler and others, 1981), are probably caused by excess argon. Field relationships discussed in this report suggest that the intermediate plutonic rocks and the mafic-ultramafic rocks are, in part, contemporaneous, and thus the bulk of the gabbroic rocks are probably Early to Middle Jurassic in age.

PETROGRAPHY

Because many of the gabbroic rocks on the Nelchina transect are highly altered, a brief description of the unaltered gabbroic rocks of the Nelchina River Gabbonorite follows. A more detailed discussion of the gabbroic rocks is found in Burns (1983).

In the typical gabbonorite of the Nelchina River Gabbonorite, plagioclase is commonly unzoned or only

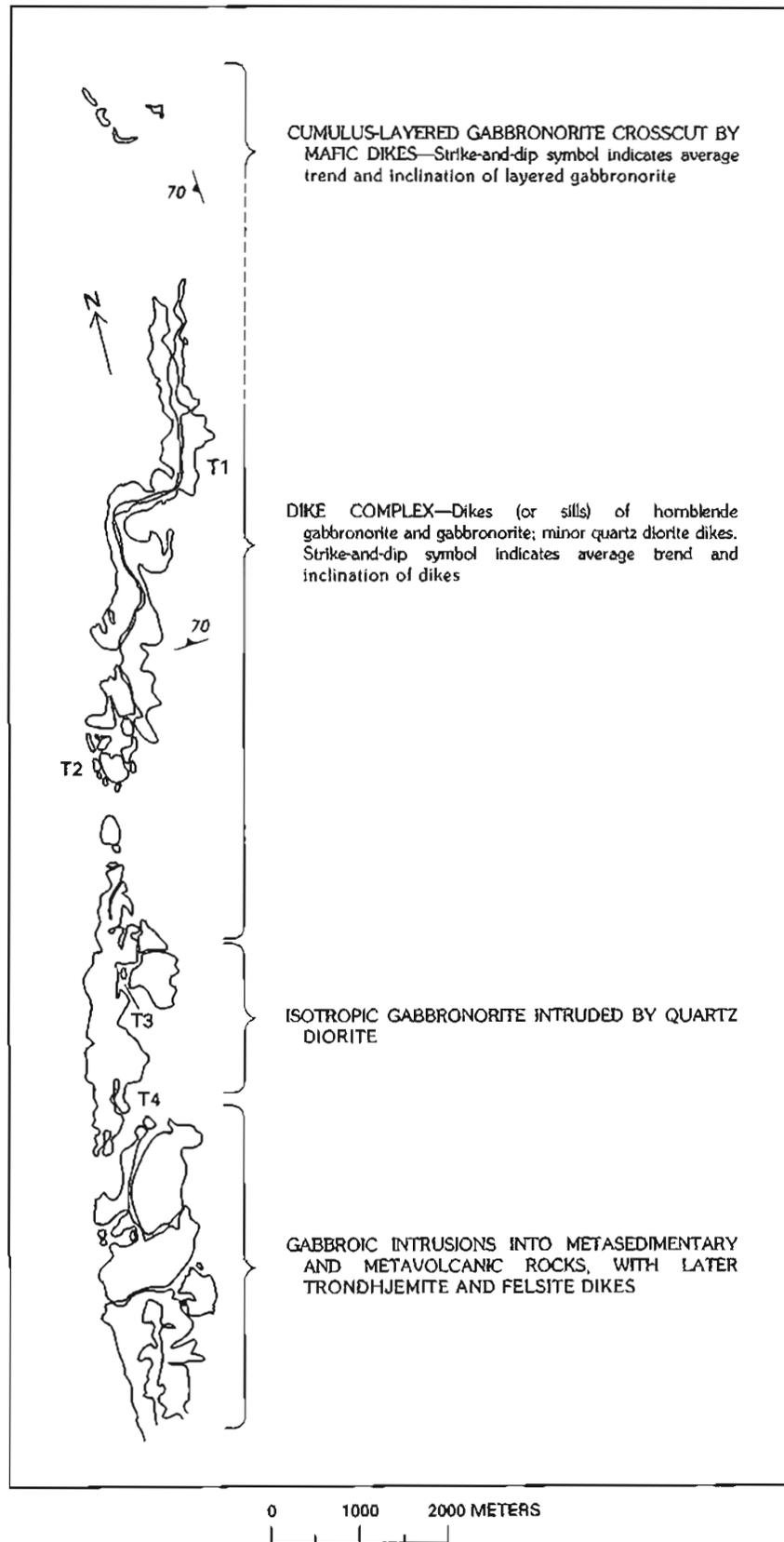


Figure 3. Diagrammatic representation of Nelchina transect of the Nelchina River Gabbro-norite, showing four major lithologic groups and reference locations T1 to T4 (see text). Brackets are dashed where transition between lithologic groupings is uncertain.

slightly zoned. Plagioclase composition within most of the body ranges from An_{65} to An_{95} (Burns, 1983). Orthopyroxene is ubiquitous and is about equal to clinopyroxene in abundance. Orthopyroxene typically exhibits pink-green pleochroism; optical and limited microprobe data suggest compositions of approximately $En_{63-77}Fs_{21.5-37}Wo_{0-1.5}$. Thin clinopyroxene exsolution lamellae are common in most orthopyroxenes. Electron microprobe analyses given elsewhere (Burns, 1983, 1985) indicate that the clinopyroxene crystals are diopside, salite, and calcic augite. Thin orthopyroxene exsolution lamellae are present in about half of the clinopyroxene crystals.

Most hornblende in the gabbroic rocks is pargasitic and is pale greenish tan to light brown. The pargasitic hornblende typically forms less than 5 percent of the rock and is most common as reaction rims around clinopyroxene. The pargasitic hornblende is inferred to be a late-magmatic phase or the result of high-temperature reequilibration that took place shortly after crystallization.

Gabbronorites containing 10 to 40 percent magnesian hornblende are present on the Nelchina transect and in the western part of the Nelchina River Gabbronorite. These rocks are discussed in detail in this paper.

Primary magnetite and ilmenite are common in the gabbronorites and magnetite gabbronorites of the Nelchina River Gabbronorite. Modal abundance of magnetite and ilmenite ranges from 0 to 15 percent, but most gabbronorites contain from 2 to 6 percent opaque minerals. The presence of thin lamellae of ilmenite in magnetite suggests oxidation exsolution.

Deuteric-alteration assemblages are ubiquitous in the Nelchina River Gabbronorite. The alteration appears to have encompassed a wide range of temperatures and suggests slow cooling of the gabbroic rocks. Mineral compositions and assemblages of the rocks composing the Nelchina River Gabbronorite suggest reequilibration at temperatures similar to granulite through lower amphibolite-upper greenschist conditions (Burns, 1983). The rocks in the Nelchina transect largely contain amphibolite and greenschist assemblages (see section "Alteration and Veining of Gabbroic Rocks").

NELCHINA TRANSECT

Four major lithologic groups of the Nelchina River Gabbronorite were mapped in the Nelchina transect (fig. 3; pl. 1). From north to south these are (1) cumulus-layered gabbronorite and mafic dikes, (2) dike-complex rocks (layered rocks produced by multiple intrusions of gabbroic and quartz dioritic magmas), (3) isotropic gabbronorite intruded by quartz diorite, and (4) gabbroic intrusive rocks and their metasedimentary and metavolcanic host rocks with later trondhjemite and felsite dikes. Extensive deformation, alteration, and veining are superimposed on the

Nelchina River Gabbronorite (pls. 1 and 2). However, numerous areas of less-altered gabbroic rocks, common preservation of primary mineral textures, and detailed studies of pyroxene-alteration products permit the determination of original rock types. The four different major lithologic groups are described below; map-unit symbols given in parentheses are from plate 1.

CUMULUS-LAYERED GABBRONORITE AND MAFIC DIKES

CUMULUS-LAYERED GABBRONORITE (Jncl)

Cumulus layers composed dominantly of rusty-weathering gabbronorite crop out at the north end of the Nelchina transect (fig. 3). [The terms "cumulus," "adcumulus," and "mesocumulus" are used in this report in the sense of Irvine (1982) as textural terms suggesting only that the rock formed by fractional crystallization; they are not meant to imply formation by crystal settling in a magma chamber.] Layers defined by significant modal variations in orthopyroxene, clinopyroxene, and plagioclase are as much as 5 m in thickness. Fine-scale phase and modally graded layers, 1 to 3 cm thick, are also common (fig. 4). Anorthosite layers 1 cm wide are abundant. The thin layers are lens-shaped in cross section with a typical width of less than 10 m. Erosional unconformities, scour channels, and graded beds—considered typical of crystal settlements and magmatic currents—are not present among the layers.

The gabbronorites have mesocumulus to adcumulus textures and contain 15 to 30 percent orthopyroxene (ferrobronzite-hypersthene?), 15 to 30 percent clinopyroxene (augite), and 40 to 65 percent slightly zoned calcic plagioclase (bytownite). Both pyroxenes have abundant, fine exsolution lamellae of pyroxenes. Amphibole (probably magnesian hornblende, pargasite, or varieties of pargasitic hornblende) forms roughly 10 percent of the rock and is pale greenish tan in thin section. The hornblende forms thick rims on clinopyroxene crystals, narrow rims on orthopyroxene crystals, and abundant, optically continuous blebs within clinopyroxene crystals. Minor amounts of interstitial magnetite and ilmenite are common in the gabbronorites.

Alteration in the gabbronorites probably occurred during two periods. The earlier, higher temperature phase affected many of the gabbronorites in the Nelchina River Gabbronorite; this presumably deuteric alteration is characterized by the formation of cummingtonite/anthophyllite, fine-grained magnetite from orthopyroxene, and minor clinozoisite from plagioclase. At lower temperatures, actinolite (apparently magnesium rich on the basis of its pale color) and magnetite formed from clinopyroxene. Actinolite is absent from most of the mas-

sive and cumulus-layered gabbronorites elsewhere in the Nelchina River Gabbronorite; its presence in the transect suggests that these cumulus-layered gabbronorites had more low-temperature alteration than is typical elsewhere in the formation.

Most of the cumulus-layered gabbronorites in the transect are characterized by two types of deformation textures. The earliest deformation produced bent plagioclase and pyroxene crystals and thus probably occurred at moderate temperatures. Formation of all secondary fibrous amphiboles appears to have occurred after the early deformation as indicated by unfractured actinolite and cummingtonite/anthophyllite present in the previously bent pyroxene crystals. Later, brittle deformation produced fractured plagioclase grains, broken fibrous amphiboles, and abundant deformation lamellae in pyroxenes. Such textures typify the gabbronorite from areas where massive, brittle deformation occurred (Burns and others, 1983).

MAFIC DIKES (Jnmd) CROSSCUTTING CUMULUS-LAYERED GABBRONORITE

At least two generations of fine-grained mafic dikes crosscut the cumulus-layered gabbronorite. The dikes of both generations appear to have the same mineralogy. The dikes are composed of fine-grained primary hornblende and plagioclase. The plagioclase is zoned, has a bimodal grain-size distribution, and is relatively unaltered. Optical methods indicate a plagioclase composition of An_{50-60} . Cores of some of the larger plagioclase crystals were probably more calcic but are now altered to clinozoisite and epidote. Overgrowth by secondary albite(?) on the edges of the zoned plagioclase crystals is common. Hornblende in the dikes is green to greenish tan and is generally present as subhedral crystals. Magnetite and ilmenite typically compose 5 to 10 percent of the rock and are present as interstitial anhedral clots and as subhedral crystals. Re-

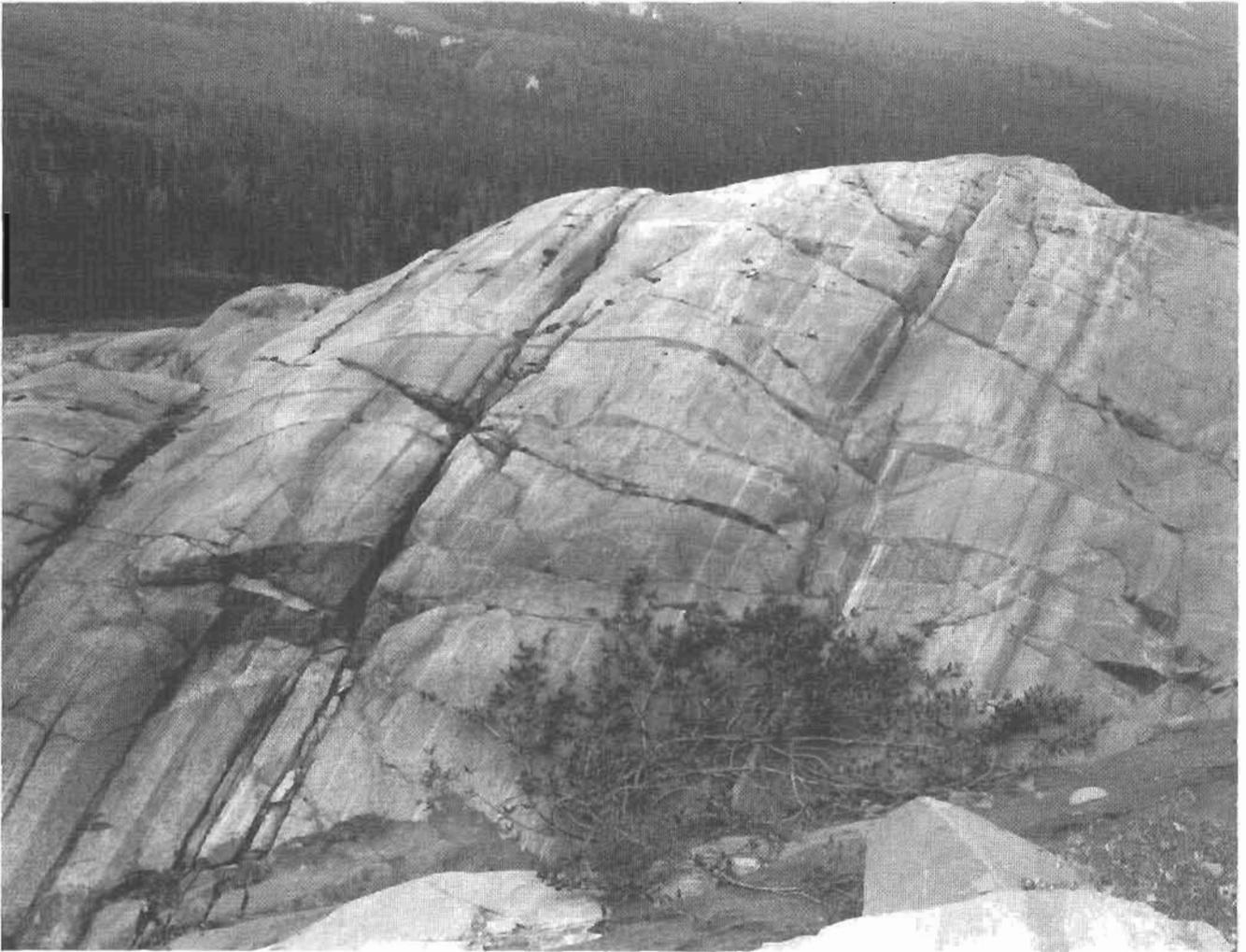


Figure 4. Fine-scale phase and modally graded layers defined by variations in pyroxenes and (or) plagioclase, in cumulus-layered gabbronorite, north end of transect. Narrow mafic dikes crosscut layering; minor offset across dikes is common. Outcrop is 5.5 m wide. View to northwest. Photograph by G.H. Pessel.

orite are exposed over an area that extends 1,500 to possibly 2,100 m in length and 600 m in width; the width is limited by the narrow exposure (fig. 6). This complex consists entirely of dikes (including sills, as used in this report) with few or no intervening screens of previously crystallized cumulus gabbronorite. All inclusions and internal banding are subparallel to the walls of the intrusions. Most of the dike rocks have equigranular textures, but a few of the gabbronorites have porphyritic plagioclase.

The oldest dikes are composed of fine-grained gabbronorite; successively younger intrusions consist of increasingly coarse-grained gabbronorite, quartz diorite, and tonalite, except for a few fine-grained mafic dikes that intruded late in the formation of the dike complex. In terms of mineralogy and characteristic field relations, each type of gabbroic dike rock is gradational to the gabbroic dike rock intruded next in the sequence. The dike rocks are discussed later in the order of their intrusion—based on cross-cutting relationships—from oldest to youngest.

FINE-GRAINED GABBRONORITE AND HORNBLLENDE GABBRONORITE (Jnfg)

Fine-grained (0.1-0.25 mm) gabbronorite and hornblende gabbronorite constitute the oldest recognizable unit

in the dike complex; the age relations are based on the apparent absence of host rock for this intrusive unit and the presence of the fine-grained rock as a common inclusion in many of the other intrusions. These rocks typically are dark green from chloritic alteration. Textures are obscure in hand specimen because of weathering, fine grain size, and chloritization. Gradational contacts between the fine-grained gabbronorite (Jnfg) and the podiform hornblende gabbronorite (Jnpg) suggest that the fine-grained gabbronorite unit is a variation of the podiform hornblende gabbronorite unit (see section "Podiform Hornblende Gabbronorite"). The pods of coarse crystals characteristic of the otherwise fine-grained podiform hornblende gabbronorite are absent or very poorly developed in the fine-grained gabbronorite unit. The gradational contacts and the grain size of the fine-grained gabbronorite suggest that the unit formed in nearly the same manner as the podiform hornblende gabbronorite unit, that is, as multiple narrow dikes (see section "Features Suggesting Intrusion of Fine-Grained Gabbronorite as Dikes").

Petrographic study indicates that these rocks originally contained 15 to 25 percent orthopyroxene (hypersthene?), 15 to 25 percent augite, 40 to 60 percent plagioclase, 0 to 20 percent hornblende, and 4 to 8 percent primary postcumulus magnetite and ilmenite. Orthopyroxene, clinopyroxene, and plagioclase are typically subhedral, but

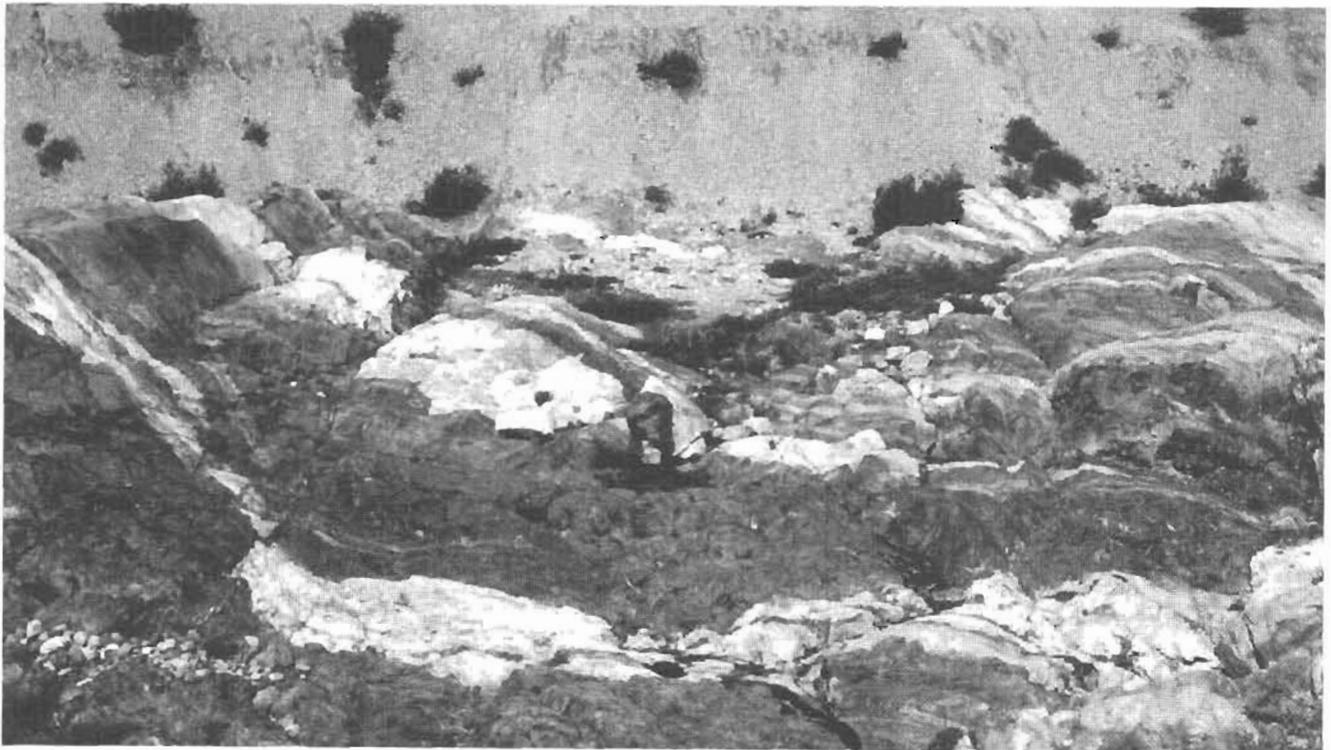


Figure 6. View of part of dike complex. Longest dimension of outcrop is about 100 m. White layers are 3- to 5-m-wide dikes composed of leucocratic gabbronorite dikes or quartz diorite. Dark layers are composed of multiple fine-grained gabbronorite dikes (mostly podiform hornblende gabbronorite). View to north with moraine in background.

placement of these oxides by pyrite is common. Minor amounts of quartz are present in a few of the dikes.

The dikes showing effects of plastic deformation (fig. 5) and flow banding are inferred to have intruded as part of the earlier generation. Near the margins of these dikes, the layering of the host gabbroic rock is similarly deformed, apparently by intrusion of the dikes (fig. 5). The early deformation textures seen in thin section in the gabbronorite probably resulted from intrusion of the dikes, as the bent pyroxene and plagioclase crystals suggest ductile behavior of the crystals at moderate temperatures. The layered gabbronorite must have been close to solidus temperatures when the mafic dikes intruded. Also, pargasitic(?) hornblende in these gabbronorites is more abundant than is typical of other gabbronorites of the Nelchina River Gabbronorite; its abundance suggests an addition of water at an early stage of the cooling history of the gabbronorite. The plastically deformed hornblende gabbro dikes may have been the source for the early water or may have been conduits for the water that formed the relatively abundant hornblende in the gabbronorites.

Other fine-grained mafic dikes in this area do not show effects of plastic deformation and are thought to have intruded when the gabbroic rocks were relatively cool. Intrusion of the dikes may have contributed to the gabbronorites' brittle deformation evident in such textural features as fractured plagioclase and cummingtonite-anthophyllite crystals (see section "Cumulus-Layered Gabbronorite"). The intrusions of these dikes may also have induced the formation of the abundant actinolite in the surrounding gabbronorite. Small (0.5 m), right- and left-lateral offsets in layering across the dikes are common (fig. 4).

DIKE COMPLEX—LAYERED ROCKS PRODUCED FROM MULTIPLE INTRUSIONS OF GABBROIC AND QUARTZ DIORITIC MAGMAS

Layered rocks produced by multiple sheet intrusions of gabbronorite, hornblende gabbronorite, and quartz di-

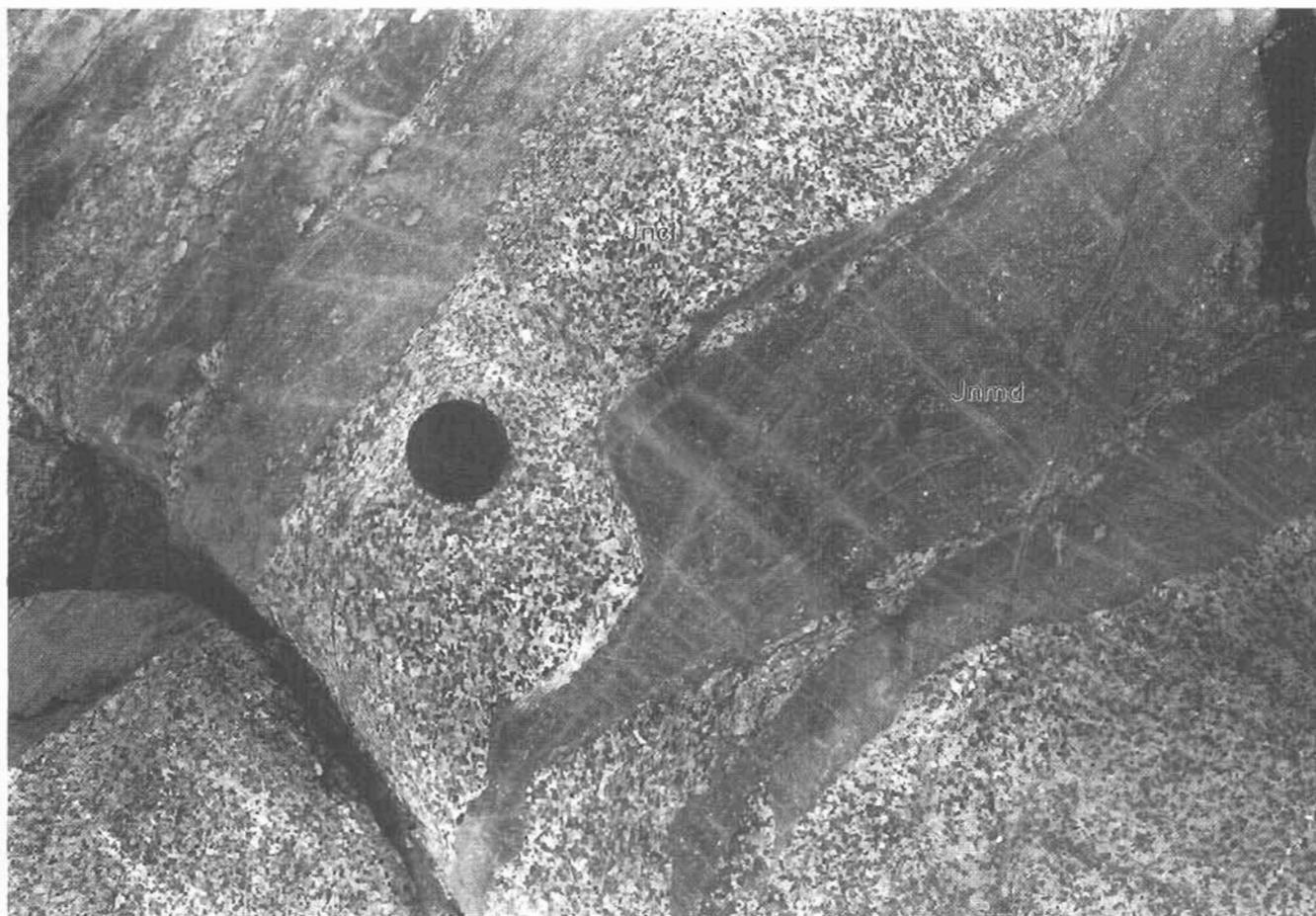


Figure 5. Fine-grained mafic dikes in cumulus-layered gabbronorite showing flow foliation and plastic deformation. Textures in cumulus-layered gabbronorite are similarly deformed, and pyroxenes are largely altered to hornblende. Lens cap is 7 cm in diameter. Photograph by G.H. Pessel.

MIXED GABBROIC ROCKS (Jnmx)

The mixed gabbroic rocks unit is composed of medium-grained gabbronorite and hornblende gabbronorite that formed during one or more intrusive events; this unit commonly contains abundant inclusions of fine-grained gabbronorite (fig. 9). The textures in the unit are identical to schlieren textures of migmatites (Mehnert, 1968). However, field relationships suggest that the migmatitic-appearing textures formed by multiple intrusion and flow and not by partial melting of preexisting rock as the term often implies (Mehnert, 1968). The textures of the mixed gabbroic rocks unit are gradational with those in the podiform hornblende gabbronorite (Jnpg) and in the inclusion-rich gabbronorite dikes (unit Jnigi).

The mixed gabbroic rocks unit is characterized by a wide variation in grain size (fig. 9). Lenses (1-2 cm wide) of coarse hornblende, plagioclase, magnetite, and ilmenite—resembling those in the podiform hornblende unit (Jnpg)—and abundant lenticular inclusions of fine-grained gabbronorite and hornblende gabbronorite (Jnfg) are sur-

rounded by medium-grained gabbronorite and hornblende gabbronorite. Flow(?) foliation is common. Although most of the unit apparently resulted from a single intrusion, the medium-grained gabbronorite appears to have been emplaced locally as several intrusions. Diffuse and gradational dike walls may obscure distinctions between individual intrusions of medium-grained gabbronorite elsewhere in the unit. The unit is typically light gray with dark-gray inclusions, but green chloritized rocks are also present.

BANDED GABBRONORITE (Jnbg)

The gabbronorite with banded structure is composed of dark-weathering, fine-grained gabbronorite intruded by coarser grained, lighter-weathering gabbronorite dikes (fig. 10). The two types of gabbronorite typically form parallel bands, 2 to 3 cm thick, and have sharp contacts. The coarser grained dikes have extremely narrow, chilled borders and clearly crosscut the finer grained rock.



Figure 7. Podiform hornblende gabbronorite. *A*, Subparallel lenticular pods of coarse hornblende, magnetite, ilmenite, and plagioclase. Hammer for scale. Photograph by G.H. Pessel. *B*, Subparallel bands of coarse hornblende, magnetite, ilmenite, and plagioclase superimposed on lighter colored hornblende gabbronorite. Hammer for scale.

The banded gabbronorite unit is similar to the mixed gabbroic rocks unit (Jnmx) in that both units contain fine-grained gabbronorite intruded by medium-grained gabbronorite. However, the mixed gabbroic rocks unit shows a range of grain sizes and probably has many diffuse contacts, whereas the banded gabbronorite unit contains only two grain sizes and has no gradational contacts.

MEDIUM-GRAINED ISOTROPIC GABBRONORITE DIKES (Jnigi, Jnigd)

Medium-grained gabbronorite dikes, 3- to 5-m wide (fig. 6), crosscut and intrude the podiform hornblende gabbronorite unit (Jnpg). Most of the white-weathering dikes are composed of plagioclase (70-85 percent), pyroxenes (10-30 percent), hornblende (0-10 percent), and opaque minerals (0-4 percent) and are probably small bodies of the isotropic gabbronorite unit (Jnig). Some of the dikes may be dioritic in composition. These gabbronorite dikes typically have sharp

contacts and fingerlike apophyses into the surrounding podiform hornblende gabbronorite (fig. 11). The locally gradational contact on the north side suggests diffusion of aqueous solutions across this boundary.

Dikes contain varying amounts of inclusions, and some dikes have none. The grain size and possibly the abundance of the plagioclase increase as the number of inclusions decreases. Inclusions in these dikes commonly are sheets, 30 cm wide, that consist of the podiform hornblende gabbronorite unit (Jnpg; fig. 12). Dikes with few or no inclusions typically have pegmatitic cores composed of coarse hornblende and plagioclase.

Secondary minerals include cummingtonite, anthophyllite, clinozoisite, epidote, chlorite, sphene, and pyrite.

QUARTZ DIORITE AND TONALITE (Jnqd)

Quartz diorite and tonalite intruded the dike complex as narrow (less than 4 m thick) dikes (fig. 6), typi-

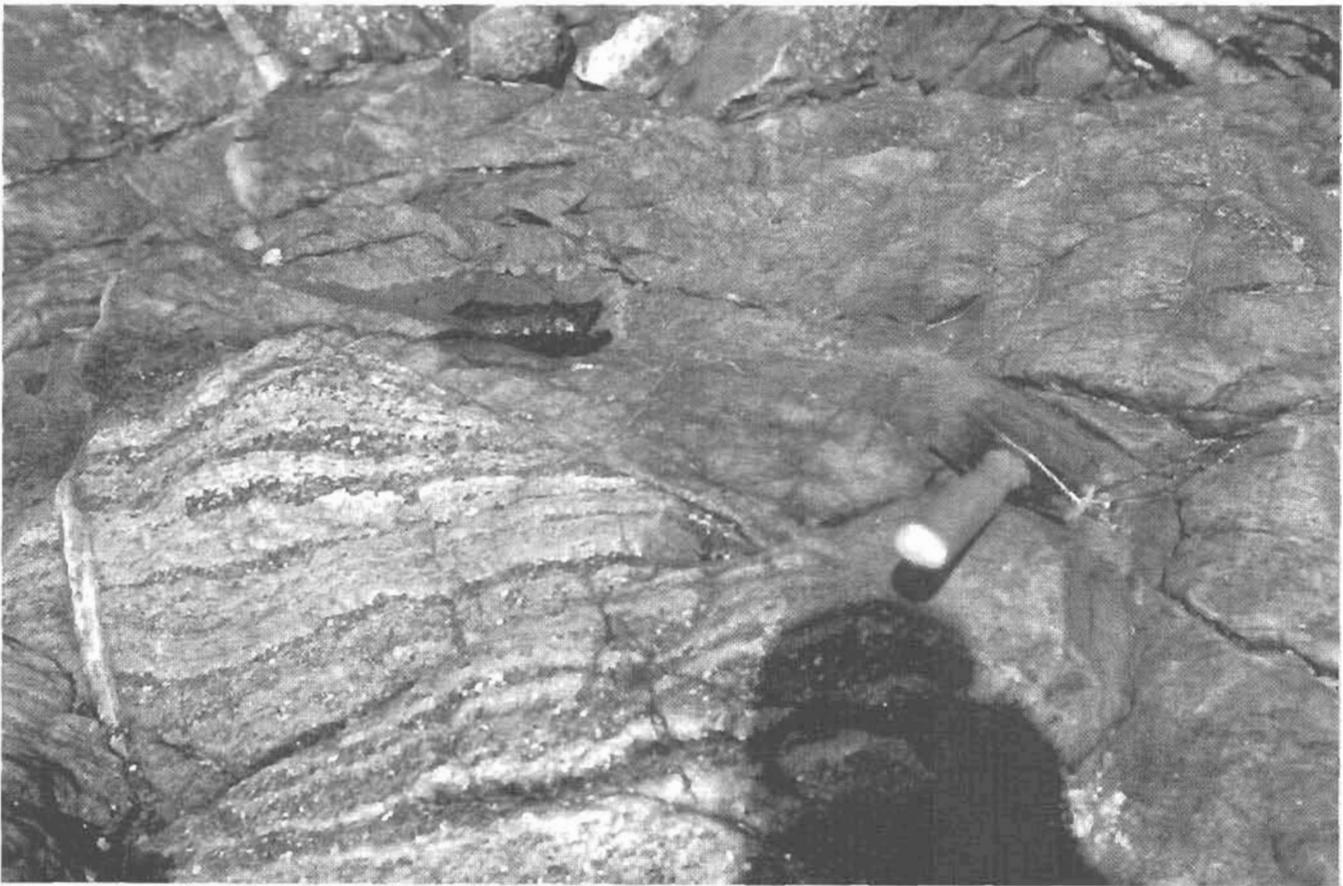


Figure 7. Continued.

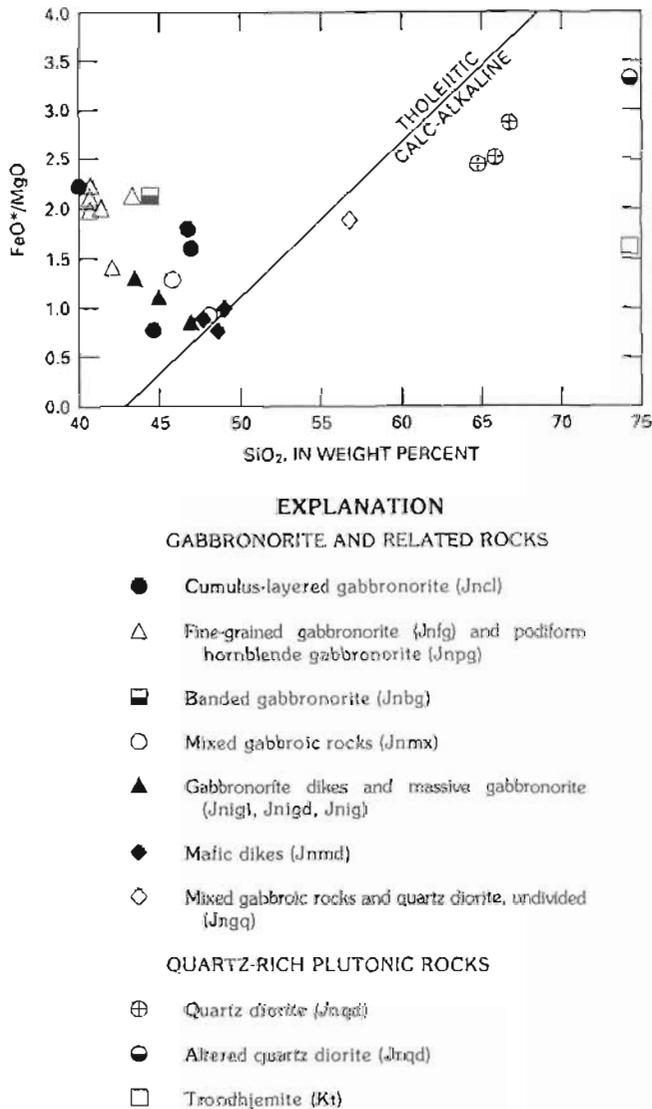


Figure 8. Variation of SiO_2 with FeO^*/MgO (bulk-compositional data) for rocks of the Nelchina River Gabbrocorite. Analyses were corrected for loss on ignition and H_2O^- and were normalized to 100 percent. FeO^* , total iron as FeO . Line for distinguishing between tholeiitic and calc-alkaline trends from Miyashiro (1974).

cally subparallel to the foliation in the gabbroic rocks. One small quartz diorite and tonalite body, with apophyses parallel to the foliation in the gabbroic rocks, is present in the southern part of the dike complex. The quartz content is variable, and no attempt was made in the field to distinguish between tonalite and quartz diorite. These rocks will hereafter be referred to as quartz diorite.

The quartz diorite is medium grained, light gray, and bleached white where altered. A greenish tint (due to chloritization) and spotty limonite staining accompanies the bleaching. Unaltered quartz diorite is composed of plagioclase (40-65 percent), quartz (15-30 percent), and hornblende (10-25 percent), with minor amounts of opaque phases. K-feldspar is not present. Most quartz grains are

blue in hand specimen and are typically interstitial. Inclusions of small rods of apatite are common. Plagioclase, typically subhedral, appears to be slightly zoned, but strain produced by deformation makes this difficult to determine. Green hornblende forms medium-grained (1-4 mm), subhedral crystals.

Alteration of the quartz diorite is extensive. Plagioclase is altered to clinozoisite, albite, and commonly small amounts of fine-grained epidote and white mica. The plagioclase alteration assemblage in the quartz diorite is thus commonly distinct from the alteration assemblage in the gabbroic rocks, which does not include white mica. In more intensely altered quartz diorites, hornblende is partly or completely replaced by chlorite. Actinolite, a common low-temperature alteration product of hornblende, is not present.

A quartz-albite rock with less than 10 percent mafic minerals (dominantly hornblende altered to chlorite) is commonly present near the center of quartz diorite dikes and is in gradational contact with the quartz diorite. Locally the dike centers are pure quartz. The quartz-albite

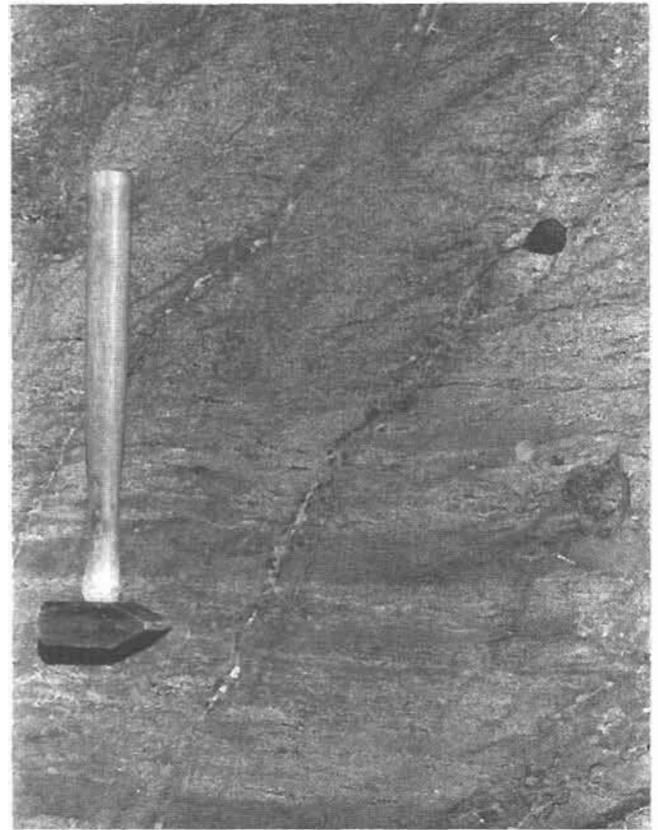


Figure 9. Mixed gabbroic rocks unit (JnmX) showing lenticular inclusions of dark gray, fine-grained gabbrocorite and small coarse-grained pods (lenses) in light gray weathering, coarser grained gabbrocorite. Note similarity to podiform hornblende gabbrocorite (Jnpg). Photograph by C.H. Pessel.

rock could be a leucocratic phase of the quartz diorite; however, it always bears chlorite and minor amounts of pyrite and is limonite stained. These observations suggest that this quartz-albite rock is an alteration product of the quartz diorite. The mineralogy and chemical composition of the quartz-albite rock closely resemble those of the trondhjemite dikes. The possibility that some of these leucocratic quartz diorites are trondhjemites that have intruded the quartz diorite and (or) gabbroic rocks cannot be entirely dismissed. This problem is discussed more fully in the section "Gabbroic Rocks, Metasedimentary and Metavolcanic Rocks, Trondhjemite, and Felsite."

Contacts between the quartz diorite and the gabbroic rocks in the dike complex are sharp to gradational. A small amount of interstitial quartz is commonly present in the gabbroic rocks adjacent to the quartz diorite dikes in the dike complex. Quartz is not generally present in the gabbroic rocks of the Nelchina River Gabbroic Complex. The interstitial quartz may have formed in the gabbroic rocks by diffusion of silica if the gabbroic rocks were sufficiently hot when they were intruded by the quartz diorites. Early

intrusion of the quartz diorites into the gabbroic rocks is suggested by textures seen in outcrop, such as foliation in the gabbroic rocks that is bent by dikes of quartz diorite (locations T1 and T3 in fig. 3). These textures suggest plastic movement of the gabbroic rocks during intrusion of the quartz diorite. Possible textural and structural evidence of the early intrusion of the quartz diorite is also provided by the fine-grained mafic dikes (see section "Mafic Dikes").

The small quartz diorite body in the southern part of the dike section (location T2 in fig. 3) contains abundant ovoid xenoliths of gabbroic rocks that also appear to have been plastically deformed (fig. 13). The xenoliths are composed of fine- and medium-grained gabbroic rocks and are oriented approximately northeast-southwest, probably parallel to a direction of flow. However, imbrication of the xenoliths has not been observed. In thin apophyses of the quartz diorite body, such xenoliths have apparently been so stretched as to be almost indistinguishable as xenoliths. The medium-grained gabbroic rocks are more mafic than any other gabbroic rocks in the exposure,



Figure 10. Banded gabbroic rocks, composed of dark-gray fine-grained gabbroic rocks intruded by 2- to 3-cm-wide dikes (or sills) of coarser grained, white (gray-weathering) gabbroic rocks. Hat for scale. Photograph by G.H. Pessel.

with the exception of similar xenoliths in the gabbroic rocks just north of this quartz diorite body. The quartz dioritic and gabbroic magmas may have transported these anomalous gabbronorite xenoliths some distance from their original position.

MAFIC DIKES (Jnmd)

Fine-grained mafic dikes are common along the Nelchina transect and consist dominantly of fine-grained (0.1-0.25 mm) hornblende gabbro and hornblende

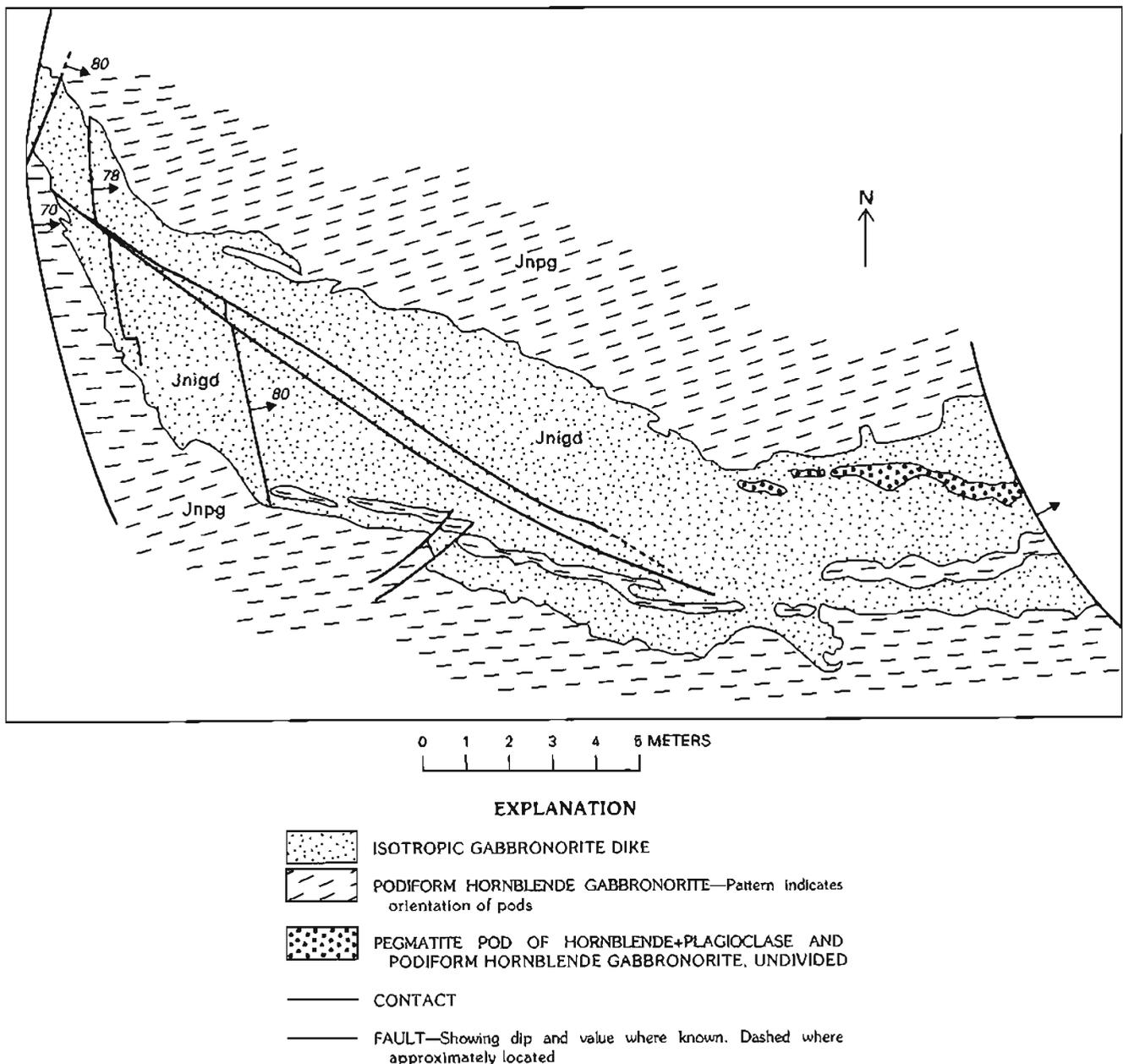


Figure 11. Detailed map of part of dike complex, showing isotropic gabbronorite dike that intruded the podiform hornblende gabbronorite unit. Gabbronorite dike contains an elongate inclusion of the podiform hornblende gabbronorite unit and a pegmatite pod composed of coarse hornblende and plagioclase.

gabbronorite. Dikes composed of hornblende, minor gabbronorite, or pyroxenite are present but not abundant. Characteristics of some hornblende gabbro dikes are discussed in the section "Mafic Dikes Crosscutting Cumulus-Layered Gabbronorite." The mafic dikes intrude gabbroic, quartz dioritic, and metasedimentary and metavolcanic rocks along the transect. The mafic dikes appear to be the most magnesium-rich rocks in the Nelchina transect, ranging from 9 to 12 weight percent MgO (table 1).

The fine-grained dikes display important textures and structures. Local folding of and boudinaged structure in the dikes imply ductile movement of the country rocks after emplacement of the dikes. Near location T2 (fig. 3), subparallel mafic dikes crosscut both gabbronorite and quartz diorite. However, the dikes are intruded by the same rocks (both gabbronorite and quartz diorite) that they appear to intrude (fig. 14). These dikes either were injected into the less mafic crystal mush, cooled, and brittlely broken while the country rock flowed around them, or, less likely, were intruded by the gabbronorite and the quartz diorite. The presence of both deformed and undeformed dikes in other areas suggests that the mafic dikes were intruded over a considerable period of time.

FEATURES SUGGESTING INTRUSION OF FINE-GRAINED GABBRONORITE AS DIKES

The large amount of fine-grained gabbronorite in the area is unusual for a large pluton. Most mafic intrusions and even basalt flows, although fine grained near their margins, become coarser grained toward their centers. The fine-grained rocks along the Nelchina transect, however, crop out discontinuously and occur as inclusions in later gabbronorite over an area at least 1,500 m long and show no coarsening of crystals near the center of this area. Quenching, perhaps due to rapid release of volatiles or rapid ascent of subvolcanic feeders and subsequent loss of pressure, may have caused the crystallization of large amounts of fine-grained rocks. However, field observations suggest that the thick sequence of fine-grained gabbronorite intruded as a series of thin dikes.

A widespread system of narrowly spaced linear fractures in the fine-grained gabbronorite is suggested some of the textural and structural features of the fine-grained gabbronorite: (1) parallel bands, 2 cm wide, intruded by coarser grained gabbronorite in the banded gabbronorite unit (Jnbg), (2) subparallel pods and continuous bands of

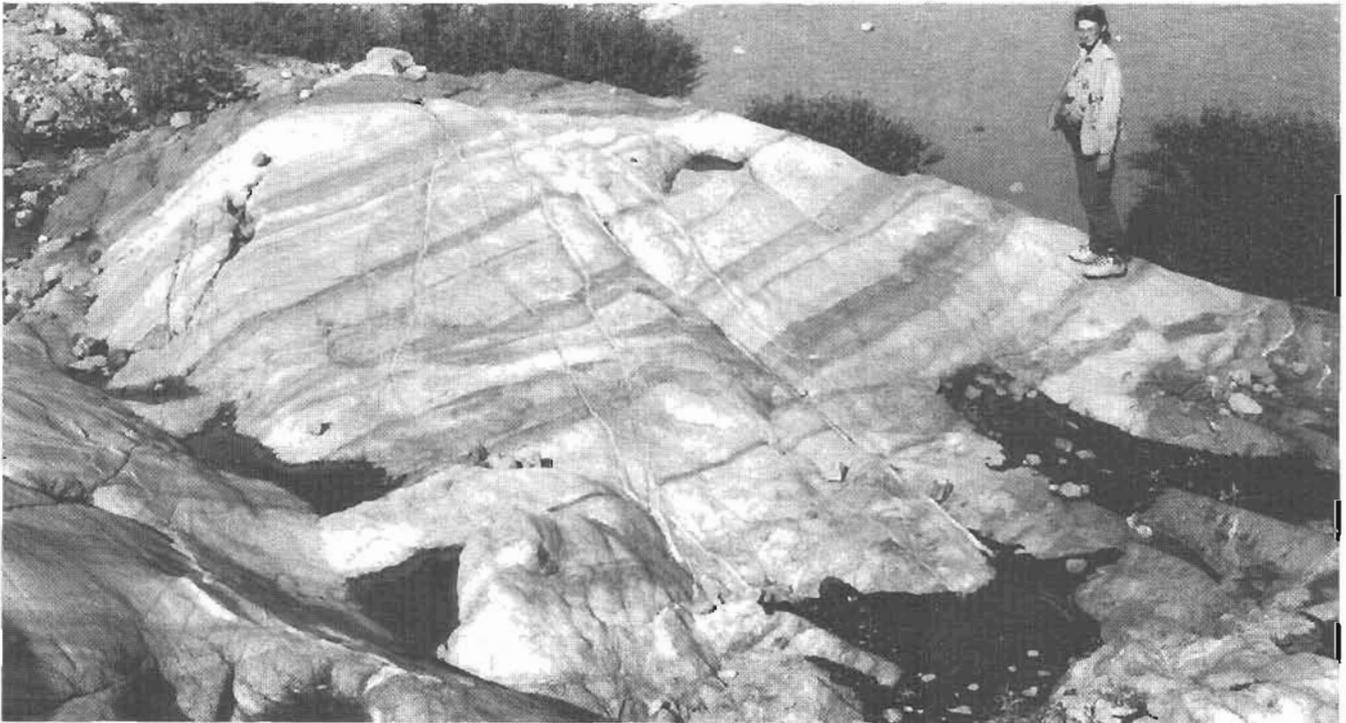


Figure 12. Light-colored gabbronorite dike (Jnigi) in central part of dike complex. Contains sheets of dark-weathering podiform hornblende gabbronorite (Jnpg). View to northeast. Photograph by G.H. Pessel.

coarse crystals in the podiform hornblende unit (Jnpg), and (3) abundant elongate, narrow inclusions of the fine-grained rock in the younger mixed gabbroic rock unit (Jnmx). These linear fractures in the fine-grained gabbronorite suggest that these rocks were emplaced as multiple narrow dikes.

Abundant aqueous solutions apparently produced the coarse pods in the podiform hornblende gabbronorite (Jnpg). After the formation of podiform hornblende gabbronorite, new magmatic intrusions formed the mixed gabbroic rocks (Jnmx), the banded gabbronorite (Jnbg), and the gabbronorite dikes (Jnigi and Jnigd). The transition from aqueous-vapor-dominated processes to dominantly magmatic activity may have occurred in a gradational manner. Whether a contact is sharp or diffuse is probably related to differences in the amount of magma as against fluid and the temperature differences between the intruding magma and the existing rock.

ISOTROPIC GABBRONORITE INTRUDED BY QUARTZ DIORITE

The third major lithologic group in the transect is composed of isotropic gabbronorite that is intruded by small plutons and dikes of quartz diorite (fig. 3). A few mafic dikes (Jnmd; see section "Mafic Dikes") are also present in this area.

GABBRONORITE (Jnig)

The isotropic gabbronorite in this area (fig. 3) is typically medium grained (2-5 mm) and massive, with almost no layering or flow foliation. White mats of clinozoisite (formed from plagioclase) stand out against the softer weathering, greenish-black alteration products of pyroxenes, giving these rocks a coarse salt-and-pepper ap-



Figure 13. Quartz diorite body (Jngq) containing abundant ovoid and stretched xenoliths of gabbronorite. View to south. Photograph by G.H. Pessel.

pearance. In addition to the common alteration products—such as clinozoisite, cummingtonite/anthophyllite, chlorite, epidote, and minor albite—fibrous actinolitic amphiboles are common in this unit and increase in abundance toward the south. These isotropic gabbronorite bodies are probably slightly younger than the isotropic gabbronorite dikes (units Jnigi and Jnigd).

QUARTZ DIORITE (Jnqd)

The quartz diorite intruding the isotropic gabbronorite is the same as the quartz diorite of the dike complex, but the quartz diorite within the isotropic gabbronorite has larger areas of the quartz-albite rocks associated with it (see section “Dike Complex—Layered Rocks Produced From Multiple Intrusions of Gabbroic and Quartz Dioritic Magmas”). The quartz-albite rocks in this part of the Nelchina transect are extensively deformed and intensely stained with spotty limonite. In some outcrops, this highly deformed rock has an almost gneissic texture, and, in thin

section, cataclastic textures are common. Quartz typically forms a fine-grained matrix around broken, strained plagioclase crystals. Quartz crystals are also strained, and some are recrystallized. Hornblendes in the quartz diorite are mostly altered to chlorite.

In areas of extensive alteration, quartz-albite rock and associated quartz-sericite-chlorite veins are abundant but typical quartz diorites are absent. Major-oxide compositions indicate that the quartz-albite rock is trondhjemitic. However, field and petrographic relationships (discussed earlier) indicate that these rocks are essentially altered quartz diorite instead of a leucocratic phase of the quartz diorite or a primary trondhjemite.

MIXED GABBROIC AND QUARTZ DIORITIC ROCKS (Jngq)

Zones of complexly mixed gabbroic rocks and quartz diorite are present near the edges of small quartz diorite bodies. The contacts are variable in character and

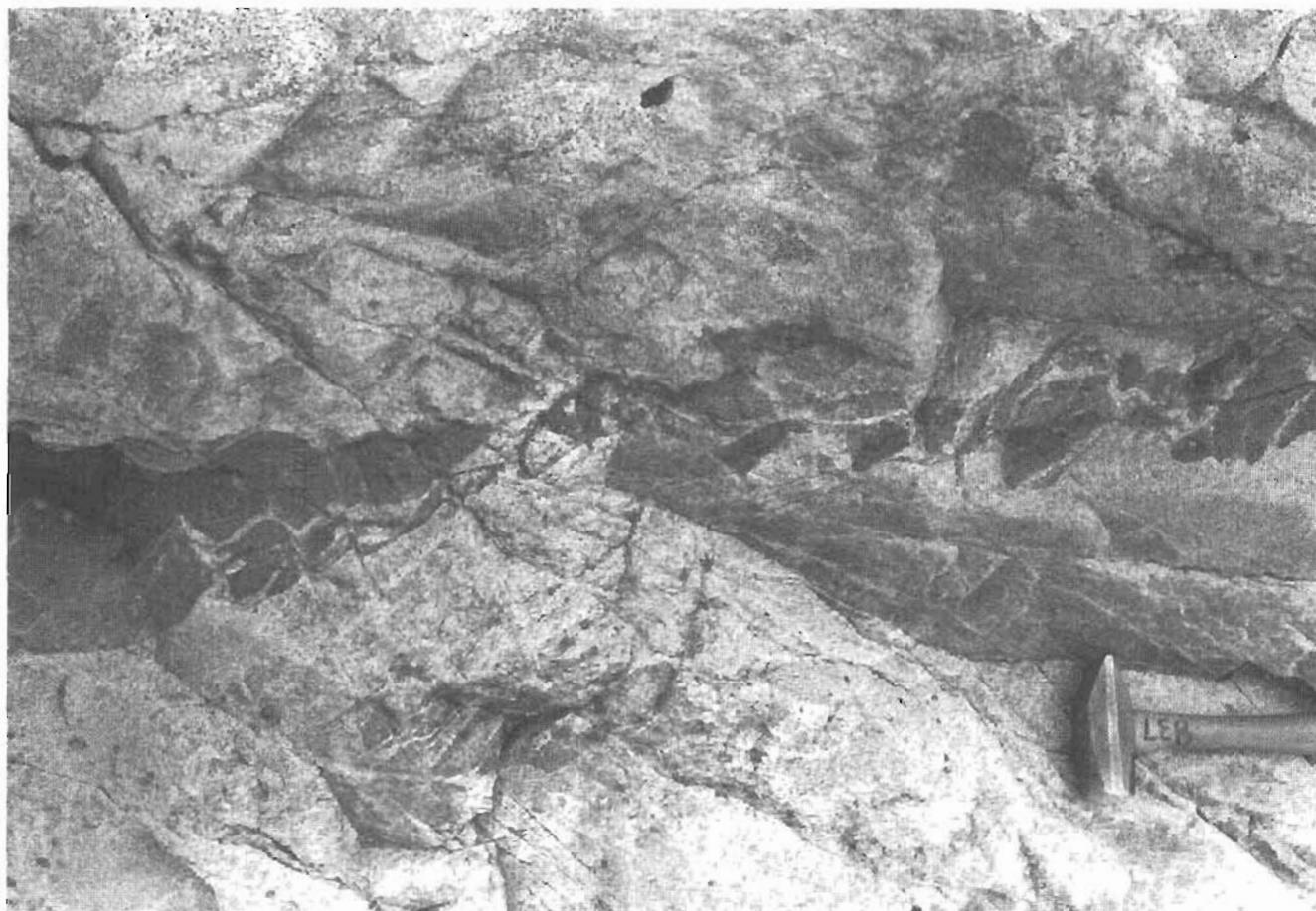


Figure 14. One of the fine-grained hornblende gabbro dikes that form discontinuous, subparallel trails in mixed gabbroic rocks unit (Jnmx) near location T2 of figure 3. (See section “Mafic Dikes” under “Dike Complex—Layered Rocks Produced from Multiple Intrusions of Gabbroic and Quartz Dioritic Magmas” in text.). Photograph by G.H. Pessel.

include both sharp and gradational boundaries; migmatitic-textured rocks in some boundary zones show the effects of plastic deformation. The most common texture consists of lenticular (stretched?) inclusions of gabbronorite in a matrix of quartz diorite, similar to schlieren textures of migmatites. Because the gabbroic inclusions commonly show plastic-deformation textures, apparently the gabbroic rocks were still hot when intruded by the quartz diorite. Some mixtures of gabbroic rocks, mafic dikes, and quartz diorite are folded (location T4 in fig. 3; fig. 15).

The mixtures of gabbroic and quartz dioritic rocks composing this unit (Jngq) texturally differ from the mixed gabbroic rocks unit (Jnmx) in that the coarse pods of hornblende, magnetite, and plagioclase characteristic of the latter are not present in the mixtures of quartz diorite and gabbronorite. Additionally, the grain size is less variable in the mixtures of quartz diorite and gabbronorite than in the mixed gabbroic rocks unit.

GABBRONORITE, METASEDIMENTARY AND METAVOLCANIC ROCKS, TRONDHJEMITE, AND FELSITE

Metasedimentary and metavolcanic rocks were intruded by gabbronorite and are present as large septa in the southern part of the map area. Gabbronorite forms both small dikes and sills in the metamorphic rocks and large sills of generally nonfoliated rock separating septa of metamorphic rocks. Locally the contact between the units is discordant (fig. 16). Narrow trondhjemite dikes, probably distinct from the quartz-albite rock discussed earlier, cross-cut both the gabbroic and the metamorphic rocks. These dikes may be related to a late stage in the formation of the Jurassic arc. The metamorphic, gabbroic, and dike rocks were then intensely deformed and subsequently intruded by felsite dikes of probable Tertiary age (Winkler and others, 1981). Carbonate veins crosscut the felsite dikes.



Figure 15. Mixture of quartz diorite and gabbronorite folded together with a large mafic dike, near contact between quartz diorite body and isotropic gabbronorite (location T4, fig. 3). Photograph by G.H. Pessel.

METASEDIMENTARY, METAVOLCANIC,
AND GABBROIC ROCKS (Jnmg)

The sedimentary and volcanic rocks are thermally metamorphosed to pyroxene hornfels grade by the gabbroic magma. This metamorphism and subsequent retrograde alteration have made determination of the protoliths uncertain. Petrographic study, however, suggests that mafic volcanic rocks (40 to 50 percent hornblende) and impure limestone are the most likely protoliths.

In this unit, septa of gneissic metamorphic rocks are separated by sills of gabbroic rocks. Contacts between the metamorphic and gabbroic rocks are diffuse and include extensive concordant migmatitic border zones. The orientation of the metamorphic fabric at the center of the septa is also concordant with the fabric of the gabbroic rocks. Thus, the mechanism of emplacement appears to involve syntectonic flow. The medium- to high-grade metamor-

phism of the metamorphic rocks and the contact features just mentioned fit the criteria for catazonal intrusions (Buddington, 1959), suggesting that the depth of emplacement for the gabbroic rocks was 10 to 20 km.

The metamorphic rocks are characterized by gneissic textures, grossularitic garnet layers, and a few thin beds of siliceous marble (probably representing recrystallized argillaceous limestones). The garnet-rich zones are generally less than 1 m wide and can be traced discontinuously for 200 m or more. Small areas of the metasedimentary and metavolcanic rocks with their characteristic metamorphic textures and minor occurrences of calc-silicate marbles are recognizable among the altered gabbroites that contain abundant disseminated magnetite (alteration map unit dm; see pls. 1, 2). The same metamorphic rocks may be present in the pervasively altered gabbroic rocks unit (Jnag) to the west, but the rocks are too sheared, deformed, and chloritized to distinguish in outcrop with certainty.



Figure 16. Thinly laminated mafic-volcanic and calcareous hornfels intruded by isotropic gabbroite near south end of transect (shown near bottom of photograph). Photograph by G.H. Pessel.

assemblage is probably related to a younger event involving extensive deformation, which probably occurred during Cretaceous time (Pavlis, 1982). Minor amounts of zeolites also are present as late-stage fracture fillings.

UPPER AND MIDDLE(?) AMPHIBOLITE ASSEMBLAGE

High-temperature deuteric alteration is represented in the gabbroic rocks by the formation of cummingtonite/anthophyllite (optical and microprobe determinations) from orthopyroxene; the coexisting altered orthopyroxene,

calcic plagioclase, diopside, and local hornblende represent the labradorite/bytownite amphibolite facies of Winkler (1974). The cummingtonite/anthophyllite appears to be more Mg rich than the coexisting orthopyroxene (table 2) and typically is accompanied by minor amounts of magnetite. This assemblage and composition suggest that the cummingtonite/anthophyllite formed from a slightly oxidizing fluid. In some gabbroic rocks, plagioclase exhibits metamorphic textures but is still relatively calcic (An_{70} , electron microprobe data); this composition also suggests temperatures correlative with amphibolite recrystallization.



Figure 17. Felsite dike (Tf) and felsitic matrix breccia dike (Tfb) crosscutting gabbroic rock (Jnig). Breccia contains clasts of felsite and country rock. Photograph by G.H. Pessel.

ALTERATION OF GABBRIC ROCKS ASSOCIATED WITH INTRUSION OF FELSITE DIKES

Some gabbroic rocks in the southern part of the map area weather to a dull black, which is apparently caused by fine-grained, disseminated magnetite. The typical alteration products in the gabbroic rocks surrounding these black-weathered rocks are chlorite, clinozoisite, epidote, and actinolite. Except for the addition of magnetite, no particular difference in mineralogy between the black gabbronorite and the surrounding gabbronorite can be discerned. This black-weathered unit is always near or contains small felsite dikes or felsitic-matrix intrusive breccia; this association suggests that the alteration is produced by oxidation associated with the felsite intrusions. Whether any chloritization is directly related to the felsite intrusions is not known.

CARBONATE VEINS

Carbonate veins, dominantly calcite±siderite(?), are also common near felsites and chloritized areas and, with the possible exception of zeolites of unknown age, are evidence of the latest stage of hydrothermal processes operating along the transect. These reddish-orange-weathering veins typically contain 1 to 5 percent pyrite and very minor amounts of base-metal sulfides. The veins generally follow major faults and in places crosscut the faults. Therefore, the observed faulting preceded the hydrothermal circulation event that produced the veins.

Weathering of pyrite contained in these carbonate veins, and to a lesser extent pyrite in the surrounding rocks, produced iron oxide that stained some of the adjacent trondhjemite dikes and quartz diorite orange. Orange staining is also present to a lesser degree in adjacent gabbroic rocks.

COMPOSITIONAL RELATIONS

The chemical compositions of rocks from the Nelchina transect (table I), which are plotted on an AFM diagram (fig. 19), indicate that the gabbroic rocks of the Nelchina River Gabbronorite are moderately iron enriched; this enrichment reflects in a general way the amount of magnetite present. The quartz diorites follow a calc-alkaline hyperthemic trend, and the rocks from contact zones between quartz diorites and gabbroic rocks plot logically between these rock types.

The gabbroic rocks are notably high in iron and low in silica, as shown by a SiO_2 versus FeO^*/MgO plot (fig. 8). Although the gabbroic rocks mostly plot on the tholeiitic side of the diagram, they do not follow a typical tholeiitic trend, which would have a slope greater than about

0.13. Additionally, the distinction in major-oxide compositional data between tholeiitic and calc-alkaline trends disappears at very low silica values (Kay and others, 1982). The extremely low silica values for the gabbroic rocks reflect the altered composition of the rocks; field evidence already discussed suggests that the rocks were altered during late magmatic events. Therefore, the gabbroic rocks cannot be classified as calc-alkaline or tholeiitic on the basis of this scheme.

SUMMARY OF EVOLUTION OF GABBRONORITES

Textures seen in outcrop are substantially different for the cumulate and dike gabbronorites; this contrast suggests that the two types formed by different methods of crystallization. Field relationships already discussed also suggest that at least two distinct major pulses of magma produced these two types of gabbronorite.

In the dike complex, plastic-deformation textures, a consistent sense of flow foliation produced during intrusion, and the multiple injections of gabbronorite suggest that the dike complex formed in a very dynamic part of the magma system. In contrast, the cumulus-gabbronorite section yields layers produced by quiescent processes; some flow layering, possibly due to moderate pressure during reequilibration, also may have been involved in their formation.

Field and mineralogical evidence also suggest that the dike complex formed from a slightly later pulse of magma than that from which the cumulus gabbronorite crystallized. Both coarse- and fine-grained gabbronorite dikes in the dike complex are parallel to the plastically deformed dikes in the cumulus gabbronorites in the transect and are perpendicular to the cumulus layers. Mineralogical similarities between the early gabbronorites in the dike complex and the deformed dikes in the cumulus gabbronorites—characterized by abundant magmatic hornblende, magnetite, and ilmenite—suggest that both were formed either during crystallization of a water-rich magma or by introduction of water (±vapor?) while the rocks were still hot. In contrast, the cumulus gabbronorite around these plastically deformed dikes contains only small amounts of magmatic hornblende, magnetite, or ilmenite. Although the Nelchina River Gabbronorite is not continuously exposed between the dike complex and the cumulates, these deformed dikes suggest that the cumulates came from an older magma, which was later crosscut by the dike complex while the cumulates were still above the solidus temperature.

During evolution of the dike complex, successively coarser grained gabbronorite intruded the existing dikes. Introduction of water appears to have lessened over time, as the later gabbroic rocks contain much less hornblende,

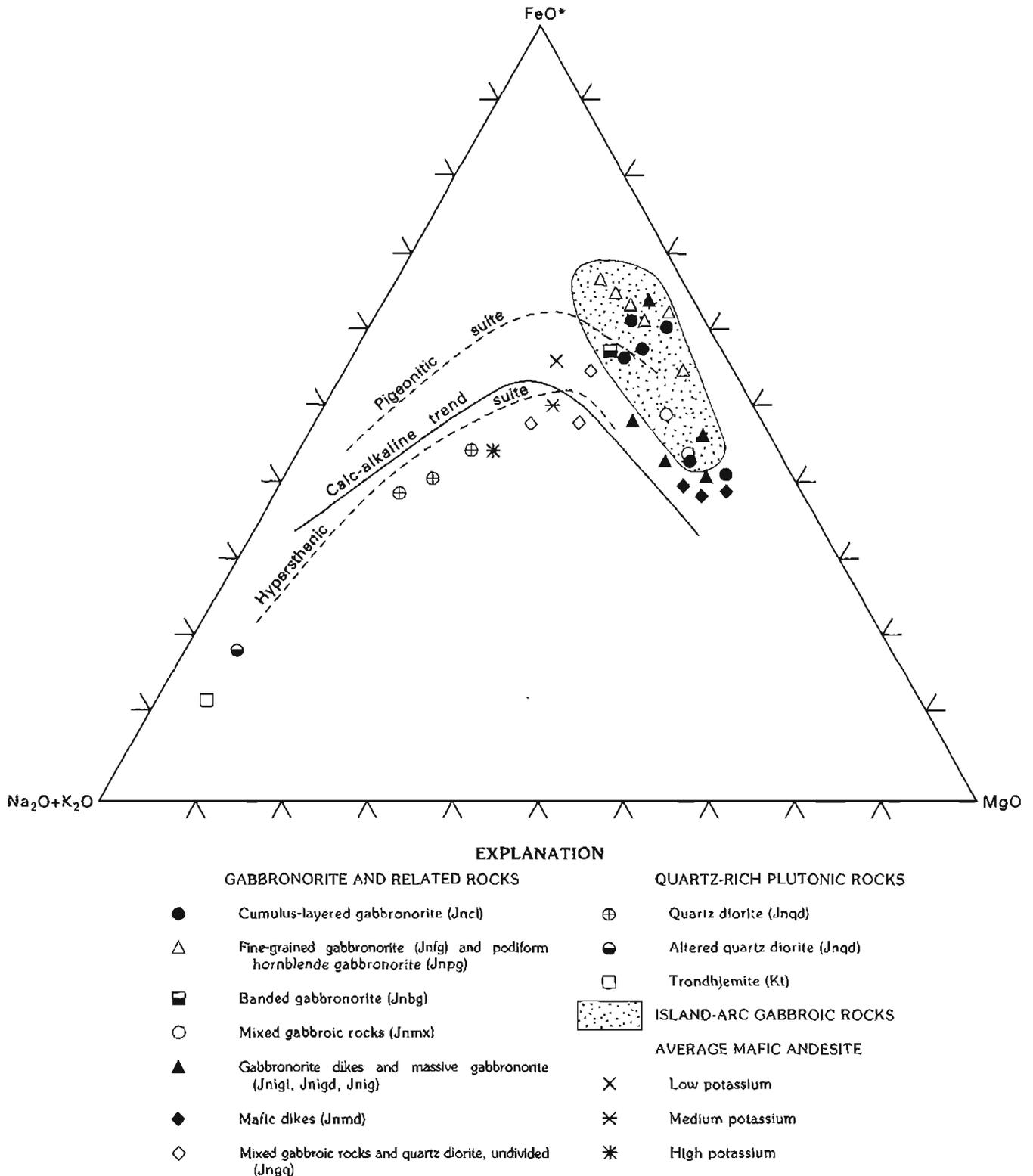


Figure 19. AFM diagram of gabbroic rocks and quartz diorites from the Nelchina River Gabbronorite. Cumulus-layered gabbronorites and podiform hornblende gabbronorites are from Nelchina transect and other parts of the Nelchina River Gabbronorite; all other rocks are from Nelchina transect only. Data from plutonic xenoliths in island arcs (shaded) taken from Aoki and Kuno (1972) and Meijer and Reagan (1981). Calc-alkaline trend (solid line) from Irvine and Baragar (1971). Pigeonitic and hypersthene rock suites (dashed lines) from Kuno (1968); average andesitic composition from Gill (1981). FeO*, total iron as FeO.

magnetite, and ilmenite. Successive intrusions are generally thicker than preceding intrusions. Also, they appear to evolve into the isotropic gabbro-norite, which crops out to the south of the dike complex; textures in the gabbro-norite in the dike complex changed over time from flow-foliated dike rock to gabbro-norite with a completely isotropic fabric.

RELATIONSHIP OF QUARTZ DIORITE TO GABBROIC ROCKS

The origin of the quartz diorites in the Nelchina transect is not understood. Extreme differentiation of gabbroic magma could produce quartz diorite and tonalite. Introduction of water into gabbroic magma and (or) a rise in oxygen fugacity could cause abundant Fe-Ti oxides to crystallize and subsequently enrich the remaining magma in silica. Differentiation of the gabbroic magma as the sole process for forming the intermediate-composition plutonic rocks is suspect owing to a volume problem. The intermediate-composition plutonic rocks form about 20 to 30 percent of the plutonic rocks in the area. Additionally, possibly a quarter of the rock mapped as quartz diorite in the northern Chugach Mountains is actually granodiorite. Whether or not differentiation of the gabbroic magma could produce this amount of moderately K-rich rocks is unknown. Furthermore, rocks compositionally between gabbro-norite and quartz diorite are found along the Nelchina transect, but detailed mapping indicates that these rocks formed by assimilation of still-warm gabbro-norite during intrusion of the quartz diorite. No rock with textures suggesting crystallization from only one magma was found to be compositionally and (or) mineralogically in between the gabbroic rocks and the intermediate-composition rocks, but this intermediate rock type may exist elsewhere in the Nelchina River Gabbro-norite. Another means of producing the calc-alkaline quartz diorite entails partial melting of a different source of either mantle or relict oceanic-crust origin.

CONCLUSIONS

Detailed mapping of the rocks along the Nelchina transect reveals that most of the layering observed formed from multiple intrusions. Field relationships generally attributed to classic layered sequences—including modally graded layers, size-graded layers, phase layering, and wispy layering—formed in the dike complex near the Nelchina Glacier as a result of multiple intrusion and probable flow. Crosscutting dikes also resemble erosional unconformities which are typically thought to represent magmatic currents. Whether the contacts among the dikes

in the dike complex are sharp or diffuse is apparently related to the amount of new magma supplied and to differences in the relative temperatures of the magma and the gabbroic rocks. The warmer the host rocks, the more diffuse the contacts of the dikes.

The Nelchina River Gabbro-norite had to evolve, at least in part, in a dynamic environment, where magmas of various compositions were produced. Evidence in the rocks of the Nelchina transect suggests that the dike complex crosscuts the cumulus-layered section and that the gabbro-norite formed from several intrusions of mafic magma. Textural relations indicate that all intrusions occurred within a relatively short time interval. Slightly later intrusions of quartz dioritic magmas were produced by (1) differentiation of the gabbroic magma, (2) drastic change in composition of the magma, possibly by the introduction of water near the magma source or by stoping and assimilation of sedimentary rocks, or (3) generation of the quartz diorite magma from a different source. The last option would have to be accomplished by a smaller degree of partial melting than is involved in the process that produced the gabbroic magma. Thus, detailed field mapping of the Nelchina transect has provided insight into possible processes that formed (1) layers in an open mafic-magma system and (2) part of the plutonic component of an intraoceanic island arc.

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Table 1. Major-oxide chemical analyses and CIPW norms for gabbroic rocks, mafic dikes, quartz diorites, trondhjemites, and felsites from the Nelchina River Gabbronorite.

[Chemical analyses were determined by XRF, with the exception of FeO which was done by titration (analyses by N.C. Veach and Kate Bull of the Alaska Division of Geological and Geophysical Surveys laboratory). FeO*, total iron as FeO; A, $(Na_2O+K_2O)/(Na_2O+K_2O+FeO^*+MgO)$; F, $FeO^*/(Na_2O+K_2O+FeO^*+MgO)$; M, $MgO/(Na_2O+K_2O+FeO^*+MgO)$; ---, not applicable or none; norm An, $an/(an+ab+or)$; norm Ab, $ab/(an+ab+or)$; norm Or, $or/(an+ab+or)$. Units mentioned in footnotes refer to map units on pl. 1]

Sample	¹ 81PE5	¹ 81BC13	² 79PE66	² 79PE36	³ 81BU1	⁴ 81BU23a	⁴ 81BU17	⁴ 81BU57
Chemical analyses (weight percent)								
SiO ₂ -----	44.69	46.93	40.04	46.74	43.48	40.76	40.77	40.90
Al ₂ O ₃ -----	22.63	18.63	16.83	18.16	20.13	18.54	17.26	17.77
FeO-----	3.96	7.63	9.43	5.66	6.93	9.41	10.10	8.48
Fe ₂ O ₃ -----	2.97	4.20	7.75	4.35	6.00	6.13	6.74	6.59
MgO-----	7.97	7.11	7.49	5.44	5.89	6.68	7.73	7.31
CaO-----	14.85	11.83	12.31	11.10	11.45	12.79	11.94	14.19
Na ₂ O-----	1.08	2.04	1.23	2.61	2.10	1.06	1.41	.65
K ₂ O-----	.10	.05	.04	.12	.04	---	.04	---
H ₂ O ⁺ -----	1.19	.61	2.36	3.86	1.17	2.12	1.51	2.06
H ₂ O ⁻ -----	.16	.14	.11	.10	.48	.53	.49	.68
TiO ₂ -----	.15	.85	1.19	.82	1.04	1.26	1.34	1.04
P ₂ O ₅ -----	.06	.11	.06	.12	.18	.08	.09	.07
MnO-----	.11	.21	.22	.19	.27	.26	.29	.16
Total --	99.92	100.34	99.06	99.27	99.16	99.62	99.71	99.90
FeO*/MgO-----	0.8	1.6	2.2	1.8	2.1	2.2	2.1	2.0
Na ₂ O+K ₂ O-----	1.18	2.09	1.27	2.73	2.14	1.06	1.45	.65
A-----	7.5	10.1	5.0	15.4	10.5	4.7	5.7	2.9
F-----	41.9	55.3	65.2	53.9	60.5	65.8	63.8	64.4
M-----	50.6	34.5	29.8	30.7	28.9	29.5	30.5	32.7
CIPW norms (weight percent)								
Q-----	---	---	---	0.6	---	---	---	---
or-----	0.6	0.3	0.2	.7	0.2	---	0.2	---
ab-----	9.3	17.3	10.8	23.2	18.2	9.2	12.2	5.7
an-----	57.4	41.7	41.7	39.3	46.5	47.3	41.6	46.9
ne-----	---	---	---	---	---	---	---	---
di-----	13.5	13.4	17.1	14.2	8.5	14.4	15.0	20.3
wo-----	---	---	---	---	---	---	---	---
hy-----	4.0	15.2	3.8	13.4	8.6	7.1	2.6	7.9
ol-----	10.4	4.1	12.2	---	6.6	10.2	15.5	7.2
mt-----	4.4	6.1	11.6	6.6	8.9	9.2	10.0	9.8
il-----	.3	1.6	2.3	1.6	2.0	2.5	2.6	2.0
ap-----	.1	.3	.1	.3	.4	.2	.2	.2
cor-----	---	---	---	---	---	---	---	---
Norm An-----	85.3	70.3	79.1	62.2	71.6	83.6	77.0	89.2
Norm Ab-----	13.8	29.2	20.4	36.6	28.0	16.4	22.6	10.8
Norm Or-----	.9	.5	.5	1.2	.4	---	.4	---

¹Cumulus-layered gabbronorite (unit Jnclg), Barnette Creek.

²Cumulus-layered gabbronorite (unit Jnclg), Nelchina transect.

³Fine-grained hornblende gabbronorite (unit Jnfg), Nelchina transect.

⁴Podiform hornblende gabbronorite (unit Jnpg), Nelchina transect.

Table 1. Major-oxide chemical analyses and CIPW norms for gabbroic rocks, mafic dikes, quartz diorites, trondhjemites, and felsites from the Nelchina River Gabbro.

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K ₂ O-----	.10	.05	.04	.12	.04	---	.04	---
H ₂ O ⁺ -----	1.19	.61	2.36	3.86	1.17	2.12	1.51	2.06
H ₂ O ⁻ -----	.16	.14	.11	.10	.48	.53	.49	.68
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F-----	41.9	55.3	65.2	53.9	60.5	65.8	63.8	64.4
M-----	50.6	34.5	29.8	30.7	28.9	29.5	30.5	32.7
CIPW norms (weight percent)								
Q-----	---	---	---	0.6	---	---	---	---
or-----	0.6	0.3	0.2	.7	0.2	---	0.2	---
ab-----	9.3	17.3	10.8	23.2	18.2	9.2	12.2	5.7
an-----	57.4	41.7	41.7	39.3	46.5	47.3	41.6	46.9
ne-----	---	---	---	---	---	---	---	---
di-----	13.5	13.4	17.1	14.2	8.5	14.4	15.0	20.3
wo-----	---	---	---	---	---	---	---	---
hy-----	4.0	15.2	3.8	13.4	8.6	7.1	2.6	7.9
ol-----	10.4	4.1	12.2	---	6.6	10.2	15.5	7.2
mt-----	4.4	6.1	11.6	6.6	8.9	9.2	10.0	9.8
il-----	.3	1.6	2.3	1.6	2.0	2.5	2.6	2.0
ap-----	.1	.3	.1	.3	.4	.2	.2	.2
cor-----	---	---	---	---	---	---	---	---
Norm An-----	85.3	70.3	79.1	62.2	71.6	83.6	77.0	89.2
Norm Ab-----	13.8	29.2	20.4	36.6	28.0	16.4	22.6	10.8
Norm Or-----	.9	.5	.5	1.2	.4	---	.4	---

¹Cumulus-layered gabbro. (unit Jnclg), Barnette Creek.

²Cumulus-layered gabbro. (unit Jnclg), Nelchina transect.

³Fine-grained hornblende gabbro. (unit Jnfg), Nelchina transect.

⁴Podiform hornblende gabbro. (unit Jnpg), Nelchina transect.

Table 1. Major-oxide chemical analyses of and CIPW norms for gabbroic rocks, mafic dikes, quartz diorites, trondhjemites, and felsites from the Nelchina River Gabbronorite—Continued

Sample	⁵ 81BU19	⁵ 81BU58	⁶ 81BU46	⁷ 81BU108	⁸ 81BU3	⁹ 81BU21a	⁹ 81BU64	¹⁰ 81BU53
Chemical analyses (weight percent)								
SiO ₂ -----	41.25	42.20	44.45	45.98	48.00	43.36	45.04	47.38
Al ₂ O ₃ -----	18.39	17.64	20.28	18.28	16.18	23.28	20.39	18.38
FeO -----	8.91	7.52	7.52	6.42	7.02	4.44	5.75	4.59
Fe ₂ O ₃ -----	5.79	5.09	4.04	3.53	2.63	3.15	2.46	2.54
MgO -----	7.18	8.35	5.23	7.36	9.90	5.52	7.35	7.82
CaO -----	13.12	14.09	10.89	12.18	10.47	13.01	12.90	14.22
Na ₂ O -----	1.30	.97	2.62	2.07	2.06	2.06	1.77	1.43
K ₂ O -----	---	.01	.12	.05	.19	.07	.13	.08
H ₂ O ⁺ -----	1.92	1.83	2.01	2.12	1.54	3.07	1.78	1.66
H ₂ O ⁻ -----	.49	.73	.65	.65	.62	.47	.67	.70
TiO ₂ -----	1.09	.66	1.01	.79	.63	.58	.74	.36
P ₂ O ₅ -----	.07	.08	.27	.09	.07	.05	.08	.09
MnO -----	.24	.15	.12	.20	.19	.14	.23	.16
Total ----	99.75	99.32	99.21	99.72	99.50	99.20	99.29	99.41
FeO*/MgO ----	2.0	1.4	2.1	1.3	0.9	1.3	1.1	0.9
Na ₂ O+K ₂ O ----	1.30	.98	2.74	2.12	2.25	2.13	1.90	1.51
A -----	5.8	4.6	10.5	11.1	10.4	14.3	10.5	9.3
F -----	62.5	56.4	60.5	50.3	43.6	48.7	60.5	42.4
M -----	31.8	39.0	28.9	38.6	46.0	37.0	28.9	48.3
CIPW norms (weight percent)								
q -----	---	---	---	---	---	---	---	0.3
or -----	---	0.1	0.7	0.3	1.2	0.4	0.8	.5
ab -----	11.3	8.5	23.0	18.1	17.9	16.5	15.5	12.4
an -----	45.6	45.2	44.8	41.7	35.3	56.5	48.9	44.6
ne -----	---	---	---	---	---	.9	---	---
di -----	16.9	21.3	7.7	16.1	14.2	8.5	13.5	21.7
wo -----	---	---	---	---	---	---	---	---
hy -----	1.1	4.1	4.6	10.1	19.3	---	5.0	15.8
ol -----	14.2	11.7	10.6	6.7	6.8	11.1	11.1	---
mt -----	8.6	7.6	6.1	5.3	3.9	4.8	3.7	3.8
il -----	2.1	1.3	2.0	1.5	1.2	1.2	1.5	.7
ap -----	.2	.2	.6	.2	.2	.1	.2	.2
cor -----	---	---	---	---	---	---	---	---
Norm An -----	80.1	84.1	65.4	69.4	64.9	76.9	75.0	77.6
Norm Ab -----	19.9	15.8	33.5	30.1	33.0	22.5	23.8	21.6
Norm Or -----	---	.1	1.1	.5	2.1	.6	1.2	.8

⁵Podiform hornblende gabbronorite (unit Jnpg), Nelchina transect.⁶Banded gabbronorite (unit Jnbg), Nelchina transect.⁷Mixed gabbronorite (unit Jnmix), Nelchina transect.⁸Isotropic gabbronorite dikes (unit Jnigd), Nelchina transect.⁹Isotropic gabbronorite (unit Jnig), Nelchina transect.¹⁰Isotropic gabbronorite (unit Jnig) contaminated by quartz diorite (unit Jnqd), Nelchina transect.

Table 1. Major-oxide chemical analyses of and CIPW norms for gabbroic rocks, mafic dikes, quartz diorites, trondhjemites, and felsites from the Nelchina River Gabbronorite—Continued

Sample	¹⁵ 818U135	¹⁶ 818U82
Chemical analyses (weight percent)		
SiO ₂ -----	74.55	60.97
Al ₂ O ₃ -----	13.32	14.73
FeO-----	.54	2.27
Fe ₂ O ₃ -----	.28	1.42
MgO-----	.49	1.82
CaO-----	1.44	6.8
Na ₂ O-----	5.30	4.13
K ₂ O-----	.99	.55
H ₂ O ⁺ -----	1.24	4.54
H ₂ O ⁻ -----	.66	.97
TiO ₂ -----	.10	.41
P ₂ O ₅ -----	.07	.14
MnO-----	.04	.08
Total-----	99.02	98.83
FeO*/MgO-----	1.62	1.9
Na ₂ O+K ₂ O-----	6.29	4.68
A-----	83.1	46.6
F-----	10.5	35.3
M-----	6.5	18.1
CIPW norms (weight percent)		
q-----	37.1	21.0
or-----	6.0	3.5
ab-----	46.2	37.4
an-----	6.9	21.5
ne-----	---	---
di-----	---	11.1
wo-----	---	---
hy-----	1.9	2.1
ol-----	---	---
mt-----	.4	2.2
il-----	.2	.8
ap-----	.2	.3
cor-----	1.1	---
Norm An-----	11.7	34.4
Norm Ab-----	78.2	60.0
Norm Or-----	10.2	5.6

¹⁵Trondhjemite (unit Kt), Nelchina transect.¹⁶Felsite (unit Tf), Nelchina transect.**Table 2.** Mole fractions of Mg/(Mg+Fe*) for coexisting orthopyroxene and cummingtonite/anthophyllite from podiform hornblende gabbronorite unit (Jnpg).

[Analyses were done by electron microprobe at the University of California, Berkeley, using well-characterized standards. Techniques were discussed by Burns (1983). Fe*, total molecular Fe]

Sample number-----	818U115	818U56
Orthopyroxene-----	72.8±0.4	65.0±2.8
Cummingtonite/ anthophyllite-----	79.4±1.7	77.7±1.9