FIELD GUIDE TO THE GEOLOGY AND MINERALIZATION OF
MAFIC LAYERED INTRUSIONS OF THE DULUTH AND BEAVER BAY
COMPLEXES, NORTHEASTERN MINNESOTA

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This trip guide is a modified from an unpublished guidebook entitled PGE Occurrences in Mafic Intrusions around Western Lake Superior, USA and Canada (Miller, Smyk, Severson, Lavigne, and Middleton, 2002). The guidebook was developed for a field trip associated with the 9th International Platinum Symposium held July 21-25, 2002 in Billings, Montana.

Geology and PGE Mineralization of the Layered Series at Duluth

The well-exposed gabbroic rocks forming the escarpment above the city of Duluth have long been recognized as the type section of the Duluth Complex. While early surveys recognized the presence of two distinct rock types in the Duluth area (Winchell, 1899), Grout was the first to interpret the layered gabbros as a product of convection and magma differentiation (Grout, 1918a-e). Taylor (1964) produced the first detailed-scale (1:24,000) geologic map of the complex in the Duluth area and defined the main distinctions between the layered and anorthositic series. Moreover, based on field, petrographic, and very limited geochemical data, Taylor recognized basic similarities between the layered series at Duluth and the Skaergaard intrusion, which Wager and Deer (1939) had established as the classic example of fractional crystallization of a tholeiitic magma. More recently, detailed mapping in the Duluth area has delineated much more about the structure and cumulate stratigraphy of the layered series (Miller and Green, 2008a & b; Green and Miller, 2008). The petrology of the layered series was summarized by Miller and Ripley (1996) and Miller and Severson (2002).

The Layered Series at Duluth (DLS) is a well-differentiated, 3- to 4.5-km-thick, east-dipping sheet-like mafic layered intrusion that is the southernmost intrusion of the Duluth Complex. Exposure is very good along the 600' escarpment above Lake Superior and the St. Louis River estuary, but is spotty inland. Aeromagnetic data show that the DLS has a north-south strike length of about 60 kilometers long and eventually pinches out into the Boulder Lake intrusion. The hanging wall of the DLS consists of olivine gabbroic and troctolitic anorthosite of the anorthositic series, which according to U-Pb dating was emplaced just prior to DLS intrusion at 1099 Ma (Paces and Miller, 1993). The footwall of the DLS at its southern end is reversed polarity lavas of the Ely's Peak basalts (Fig. 1-1). Layering and foliation in the DLS, which dip 20°-40° to the east, and modeling of aeromagnetic and gravity data indicate that the basal contact is not conformable with shallow-dipping (~15°) Keweenawan basalt flows in the footwall, but instead dips at a greater than 35° angle (Miller and Green, 2008b). Aeromagnetic data further imply that the basalt is cut out by the DLS to the north, whereupon the footwall becomes graywacke and slates of the Thomson Formation.
The DLS is divided into five major zones based on dominant rock type (Fig. 1-1). The basal contact zone is composed of coarse-grained, taxitic olivine gabbro and augite troctolite (Stop 1). The lowermost cumulate sequence is the troctolite zone (Stops 1, 2A & 2B). It is 1 to 2 kilometers thick, consists mostly of homogenous foliated troctolitic (PO) cumulates, and locally displays modal and textural layering, especially in its lower third. The cyclic zone (Stops 3, 4, & 5) forms the medial section of the DLS and is characterized by cyclical variations in cumulus mineralogy between troctolitic and gabbroic (PCFO) cumulates (Fig. 1-4). The persistent occurrence of gabbroic cumulates defines the gabbro zone (Stop 6). Gabbroic cumulates, in turn, grade upward into unlaminated (noncumulate) apatitic quartz ferromonzodiorite, which composes most of the upper contact zone (Stop 7). This quartz
ferromonzodiorite complexly mixes with a fine-grained biotitic ilmenite ferrodiorite, which ultimately forms a "chilled" contact with anorthositic series rocks (Stop 8). A body of melanogranophyre that irregularly cuts through the anorthositic series probably represents the uppermost differentiate of the DLS (Stop 9). This igneous stratigraphy is complimented by cryptic layering of cumulus mineral compositions (Fig. 1-2) and together these imply the DLS generally formed by bottom-up fractional crystallization of a moderately evolved, olivine tholeiitic parent magma.

Although the DLS is overall, a well-differentiated intrusion, the repeated progression from troctolitic to gabbroic cumulates in the cyclic zone indicates that it did not fractionally crystallize as a closed system. The cyclic zone consists of at least five macrocycles (each 50-200 m thick) within which troctolitic cumulates grade upward to gabbroic cumulates (Figs. 1-3, 1-4). Macrocycle boundaries are marked by the abrupt regression in the cumulus mineralogy from gabbroic back to troctolitic cumulates. The gabbroic parts of the macrocycles commonly contain

Figure 1-2. Igneous stratigraphy and cryptic variation of olivine, pyroxene and plagioclase composition through the layered series at Duluth. Mg values of olivine and pyroxene and An content of plagioclase are based on multiple microprobe analyses (error bars indicate one standard deviation). From Miller and Severson, 2002 (Figure 6.8).
inclusions of anorthositic series rocks and the very uppermost parts of the macrocycles locally have discontinuous layers of fine-grained gabbroic adcumulate (microgabbro). This cyclicity in phase layering does not correspond to a complimentary cryptic variation in mineral chemistry (Fig. 1-4). Based on these characteristics, Miller and Ripley (1996) suggested that the macrocyclic phase layering is predominantly related to devolatilization and decompression that attended magma venting events from a shallow (< 5 km) chamber, with magma recharge possibly having played a secondary role.

Figure 1-3. Geology of the Cyclic Zone of the DLS showing field stops 1-3 to 1-5. Note that the cumulate codes for augite are A/a rather than the C/c (clinopyroxene) used in the text.
Figure 1-4. Cryptic variation of Fo and En in outcrop samples from the cyclic zone taken along two profiles north and south of Interstate 35 (Fig. 1-3). Note that the cumulate codes for augite are A/a rather than the C/c (clinopyroxene) used in the text.

Geochemical data were acquired from 83 hand samples that profile the general stratigraphy of the DLS. The sampling focused on specific horizons, particularly in the cyclic zone, that contain visible sulfide mineralization or appear to represent perturbations to the magmatic system (Fig. 1-5, 1-6). Most of the samples have Pt+Pd concentrations below 15 ppb; 14 samples have concentrations between 15 and 150 ppb and five samples have concentrations >150 ppb. Whole rock S and Cu concentrations (Fig. 1-5) imply that the DLS magma 1) was consistently sulfide-undersaturated during troctolite-zone crystallization; 2) achieved intermittent saturation during crystallization of the cyclic zone; and 3) was fairly consistently saturated as the gabbro zone...
accumulated. In contrast to the singular large increase in Cu abundance and Cu/Pd ratio observed in the Sonju Lake intrusion (See Day 3 description), the DLS shows erratic variability in these parameters (Fig. 1-5). Such variability probably reflects the openness of the DLS system to magmatic recharge. Nevertheless, a two- to three-order-of-magnitude range in the Cu/Pd ratio through the cyclic zone indicates some level of efficiency in the ability of sulfide melt to extract PGE from silicate magma (e.g., Maier and others, 1996).

The model of magma venting to explain the phase layering of the cyclic zone (Miller and Ripley, 1996) also can explain the elevated concentrations of sulfide and PGE at cyclic zone boundaries of cumulus regression. Experimental data at low pressures (1-2 kb) suggest a positive correlation between pressure and sulfide solubility in hydrous tholeiitic magmas (Carroll and Rutherford, 1985). If valid, this implies that magma decompression due to venting from shallow differentiated magma chambers may trigger sulfide saturation (or oversaturation in a saturated magma). Devolatilization resulting from venting of a volatile-rich magma would also cause an abrupt increase in fO₂, thereby having a compounding effect on reducing sulfur solubility (Poulson and Ohmoto, 1990). The attractiveness of a magma venting as a trigger for sulfide saturation in terms of PGE enrichment is that it would promote chamber-wide sulfide segregation if the system was well mixed, or a rain of sulfide out of the roof zone if the magma chamber was compositionally zoned. Both situations would promote high R factors, though the second scenario would required enough overproduction of sulfide so as to survive the descent to the cumulate floor.
Figure 1-6. Geology of the cyclic zone of the DLS showing locations and concentration ranges of Pt+Pd from outcrop samples. (Modified from Fig. 8-12, Severson et al., 2002).
STOP 1-1: BASAL CONTACT ZONE AND LOWER TROCTOLITE ZONE, DULUTH LAYERED SERIES AND ELY’S PEAK BASALTS

Location: Railroad Grade of the former Duluth, Winnipeg, and Northern Railway, Bardon Peak, Duluth. West Duluth 7.5’ quad (T49N, R15W, Secs. 33 SE & 34 SW; approx. NAD 83 UTM – Start: 557740E, 5170300N; End: 558460E, 5170040N).

Duration: 2 hrs.

Description: This stop traverses about 400 meters of stratigraphic section of the lower part of the Layered Series at Duluth (DLS). The exposures will be accessed by walking the railroad grade from the western side of Ely’s Peak. Along the way, several extensive exposures of Ely’s Peak basalts (including a tunnel) will be encountered. The Ely’s Peak basalts form the footwall of the Duluth Complex and show the effects of intense thermal metamorphism by the gabbro. The Ely’s Peak basalts are comprised of about 1.5 kilometers of gently (10-15°) dipping, tholeiitic basaltic lavas and represent the earliest volcanic eruptions into the Midcontinent Rift.

Starting at the basal contact, which trends ~N-S in a valley between Ely’s and Bardon’s peaks, a variety of rock types belonging to the basal contact zone and the lower part of the troctolitic zone of the DLS are exposed in roadcuts and outcrops along the abandoned railroad grade as it arcs around Bardon Peak. Several macrocyclic layers grading in mode and texture are apparent in the lower part of the troctolitic zone and are thought to represent major recharge and differentiation/cooling episodes associated with the early integration stage of DLS emplacement. The exposures on the north side of the tracks are schematically shown in Figure 1-7 and areas of particular interest are flagged along the route and described below.

A. Basal Contact. The traverse starts at the irregular contact between strongly hornfelsed mafic volcanics of the Ely’s Peak basalts and taxitic olivine gabbro and augite troctolite of the basal contact zone (Flag A). Granophyre dikes cut both rock types, but display lobate contacts with the coarse gabbro suggesting two-liquid mixing. Grout (1918c) cited this mixing of granophyre and gabbro as evidence of silicate immiscibility. An alternative explanation is that the granophyre represents anatectic melts from the footwall that were not completely assimilated into the mafic magma. Contacts between the hornfels basalt and the gabbro are commonly characterized by coarse augite prisms oriented perpendicular to the contact. Roadcuts on the downslope side of the railroad grade (Flag A’) show a small, irregular intrusion of coarse gabbro into hornfels basalt.

B. Basal Contact Zone - This exposure of taxitic olivine gabbro to augite troctolite with its variable textures (medium-grained to pegmatitic, subophitic to ophitic, nonfoliated to poorly foliated) and variable modal compositions are characteristic of the basal contact zone. In contrast to other layered series intrusions along the northwestern margin of the Duluth Complex that locally contain abundant Cu-Ni(-PGE) sulfide (see Day 2 field stops), the basal contact zone of the DLS is devoid of significant sulfide mineralization.

C. Lower Macrocyclic Unit of the Troctolite Zone. Exposed here is a modally layered, medium-grained, moderately foliated, ophitic augite troctolite. This foliated POcf cumulate marks the base of the troctolitic zone and the first of three macrocyclic layers exposed along this traverse. At the east end of this exposure, the rock grades to a medium coarse-grained, augite troctolite to olivine gabbro.
Figure 1-7. Outcrop exposed along the north side of the Duluth, Winnipeg and Northern railroad grade showing variability in rock type across the basal contact zone (BCZ) and several macrocycles in the lower troctolitic zone (TZ1-3).
D. **Upper Part of Lower Macrocycle.** This exposure of medium coarse- to very coarse-grained, non-foliated to moderately foliated, ophitic to subophitic olivine oxide gabbro characterizes the upper part of the lower macrocycle (TZ1, Fig. 1-7). The exposure at D' is coarser grained and generally non-foliated.

E. **Contact between Lower and Medial Macrocycles.** Down from the grade is a sharp contact between coarse-grained non-foliated olivine oxide gabbro in a lower exposure (similar to outcrop D') and a coarse-grained feldspathic, biotitic oxide peridotite above. Following this contact upslope to the west, the peridotite gives way to a medium-grained melatroctolite overlying coarse olivine oxide gabbro. This abrupt transition from coarse olivine gabbro to medium melatroctolite is interpreted to mark a major recharge event into the DLS magma chamber. The origin of the coarse-grained oxide peridotite is unclear (see Stop 1-2A for a discussion). The oxide peridotite commonly contains trace amounts of sulfide (note local Cu staining) and has higher PGE concentrations (10-30 ppb) than surrounding rock types.

F. **Middle Section of Medial Macrocycle.** Medium- to medium coarse-grained, moderately foliated, locally layered augite troctolite is exposed in small outcrops on either side of trail leading north of tracks. These exposures occur in the midsection of the second macrocycle (TZ2, Fig. 1-7).

G. **Contact between Medial and Upper Macrocycles.** Exposures nearest the north side of the railroad grade are of massive, bitotitic coarse-grained oxide peridotite which form the upper part of the medial macrocycle (as at E). Following the flagging to an outcrop ledge, an abrupt contact is observed between the oxide peridotite and medium fine-grained, well foliated, feldspathic dunite to melatroctolite. The orientation of the contact between the feldspathic dunite and the oxide peridotite is locally irregular. It is unclear if this irregularity is due to intrusion of the peridotite into the dunite or due to scouring of the dunite into the peridotite. Evidence for both processes are found elsewhere in this area. Here and in exposures along this ledge, the feldspathic dunite/melatroctolite display a very pronounce sheet jointing formed by intense serpentine veining (Photo 1-1). Following the flagging over the top of this ledge leads to another 5-meter-high ledge outcrop that displays lenticular interlayering of troctolite and melatroctolite. Lenses of troctolite consistently thicken to the west suggesting that they may denote channel or trough layering. A similar type of lenticular (channel?) layering is more completely displayed at I, which is approximately at the same stratigraphic level. Also evident at the eastern end of this upper exposure is steeply inclined serpentine veining that refractions through the different layers.

H. **Lower Part of Upper Macrocycle.** At the beginning of a very deep cut is well layered melatroctolite grading up from the feldspathic dunite observed at G and forming the lower part of the uppermost macrocycle (TZ3, Fig. 1-7). The melatroctolite grades upward into a medium-grained, well foliated and intermittently layered, ophitic augite troctolite. At two locations (flagged as H'), the troctolite is cut by irregular steeply oriented bodies of oxide olivine gabbro pegmatite. Some have suggested that this pegmatite and the oxide peridotite are related late magmatic features.

I. **Layered Troctolite of the Upper Macrocycle.** At the highest part of the cut is an exceptional exposure of lenticular layered melatroctolite and leucotroctolite. Similar to the upper exposure at G, trough/channel structures are seemingly implied by the bowing of the layering and the consistent thickening of leucocratic layers in the axis of the trough. Several trough structures have been recognized in the Troctolitic Zone in the Bardon Peak area. The axis of the troughs tend to trend easterly (i.e., in the down dip direction of regional layering).
STOP 1-2A: LOWER TROCTOLITE ZONE, DULUTH LAYERED SERIES, DULUTH COMPLEX
(OPTIONAL)

Location: Skyline Parkway near Bardon Peak, Duluth. West Duluth 7.5’ quadrangle (T49N, R15W, Sec. 34, SW of NW; NAD83 UTM (Area E) 558540E, 5170280N).

Duration: 60 min.

Description: This stop examines rocks comprising the lower part of the Duluth Layered Series in roadcuts and barren knob exposures at the south end of Skyline Parkway. This outcrop area is approximately 500 m above the moderately dipping (~45°) basal contact of the Duluth Complex against shallow-dipping (<15°) basalt flows, which form Ely’s Peak (rocky hill to the west). This area is situated in the lower part of the troctolitic zone, but upsection of the upper exposures observed in the traverse at Stop 1-1. As seen in that section, this part of the Troctolite Zone continues macrocyclic layering of melatroctolite grading upward to coarser augite troctolite. Because the layering is similar to that seen below, it is unlikely that we will be able to visit this exposure. It is included here for those who which to return at a later date. Figure 1-8 shows the geology of the area with eight areas of interest (A-H) noted and generally described below.

The PO to OP cumulate rocks exposed at this stop include ophitic olivine gabbro, augite troctolite, troctolite, melatroctolite, and feldspathic dunite. In general, the more olivine-rich melatroctolites and dunites tend to be finer grained than the more augite-rich troctolites and olivine gabbros. These rocks display a variety of types and scales of layering. Macrocyclic layering of rock types is evident on a meter to decimeter scale—typically finer grained troctolite, melatroctolite, and feldspathic dunite upward to from coarser grained augite troctolite to olivine gabbro. Cryptic differences in olivine composition are evident with melatroctolite-feldspathic dunite being more Mg-rich (Fo62-65) compared to augite troctolite-olivine gabbro (Fo48-60). Contacts between macrocycles are abruptly (<10 cm) to narrowly gradational (<1 m) (areas C, D, and G, Fig. 1-8). Within macrocycles, various type of finer-scale layering is common. Subtle grain-size layering locally occurs in the medium- to coarse-grained augite troctolite to olivine gabbro intervals (area E). Centimeter-scale isomodal layering and decimeter-scale graded modal layering is very common in the more melatroctolitic rocks and locally has very rhythmic alternations (area F). Trough layering is locally implied by variable orientations of modal layering (areas A and C) and the tendency for the more melatroctolitic layers to pinch out along strike. However, some of what appears to be pinch out may be due to faulting along ENE-trending structures through the area (Fig. 1-8). Very abrupt reorientation and steepening of lamination in Area G suggests that some faulting may be contemporaneous with crystallization.

Deeply weathered, coarse-grained, biotitic oxide dunite to peridotite, similar to that seen at Stop 1-1 (areas E & G), occurs in two locations here (areas B and G, Fig. 1-8). Thin section of these exposures show the rock to be composed of 50-90% granular olivine, 3-20% Fe-Ti oxide (mostly ilmenite), 2-25% ophitic augite, 1-4% biotite, and 0-20% interstitial plagioclase. Primary minerals are commonly altered to chlorite, serpentine, talc, and actinolite. Olivine compositions in these bodies are Fo50-59 and therefore are similar to the augite troctolite and olivine gabbro cumulates in the area. The limited aerial extent of these oxide ultramafic bodies suggest that many may occur as small pipes or dike-like bodies. However, as seen at Stop 1-1, they also occur as stratabound subconformable lenses at olivine gabbro-melatroctolite contacts.
Ross (1985) suggested that these small oxide plugs and lenses are metasomatic replacement bodies formed by volatile fluxing out of the footwall basalts. Severson (1995; Severson and Hauck, 1990) found similar oxide ultramafic (OUI) bodies along the western and northwestern margin of the Duluth Complex to be spatially related to iron-formation inclusion and suggested that partial melting and assimilation of these inclusions may have generated the bodies. Another possible explanation is that they formed by mobilization of interstitial volatile-rich magma extracted from lower cumulates in the basal contact zone which became ponded beneath fine-grained melanotroctolite/dunite layers at the base of macrocycles. More study, especially isotopic data, are clearly needed to resolve the origin of these bodies.

STOP 1-2B: TROCTOLITE ZONE, DULUTH LAYERED SERIES AND OVERVIEW OF DULUTH COMPLEX.

*Location:* Skyline Parkway, Bardon Peak, Duluth. West Duluth 7.5’ quadrangle (T49N, R15W, Sec.34 SW; approx. NAD 83 UTM - 5170450N, 558740E).

*Duration:* 15 min.

*Description:* This brief stop, which corresponds to Area H in Figure 1-8, provides a panoramic view of the breadth of the Duluth Complex at Duluth. A 5 kilometer-thick stratigraphic section of the layered series and the overlying anorthositic series are exposed along the 200 meter high, and 15 kilometer long escarpment above the St. Louis River estuary. The top of the Duluth Complex on the rise just above downtown Duluth which is marked by a cluster of radio towers and the Enger Tower landmark. This is where our trip will end today (Stop 9). As exemplified by the layering of the troctolitic rocks exposed at this overlook, the general internal structure of the DLS dips 20-25° to the east, thus the northeast trending escarpment cuts an acute angle across the intrusion. The anorthosite series overlying the DLS can be recognized by its higher topographic expression.
STOP 1-3: CYCLIC ZONE, DULUTH LAYERED SERIES

Location: Spirit Mountain Ski Resort, Duluth. West Duluth 7.5' quadrangle (T49N, R15W, Sec 23 NW; approx. NAD 83 UTM - 5174250N, 559952E).

Duration: 30 min.

Description: About 100 m east of the north side of the ski lodge, near the top of the northernmost chairlift is a series of outcrop ledges that display over a 10-meter-thick section about 13 successive meter-scale mesocycles that mimic the decameter-scale macrocycles that characterize the medial Cyclic Zone of the DLS. Each mesocycle is composed of a medium fine grained troctolite at its sharp base with the cycle below. About 1/3 of the way up, the troctolite develops small clots (~5mm) of subpoikilitic augite and lesser oxide, which then grades on a cm-scale to a medium-grained, intergranular oxide olivine gabbro. Each mesocycle is 0.5 - 1 meter thick (Photos 1-3 & 1-4). All rocks display well developed foliation of plagioclase (in troctolite) and plagioclase and augite (in oxide olivine gabbro). Although there are slight differences in the thickness of the layers, there appears to be little difference in relative proportions of troctolitic (1/3rd) to gabbroic (2/3rd) intervals. The mesocycles fundamentally show a rapid progression from a two-phase (PO) to a four-phase (PCOF) cumulate. The mesocyclic boundaries represent even more abrupt regressions from four-phase back to two-phase cumulates.

Microprobe analyses of olivine and clinopyroxene from samples across two sharp cyclic layer boundaries near the upper part of the section show the troctolite to be somewhat more primitive than the oxide olivine gabbro. Across one interface, olivine composition changes from Fo 56.4(±0.6) in the gabbro to Fo 59.7(±0.2) in the troctolite and augite composition changes from En 69.8 (±0.9) to En 72.6 (±0.6). However, across another interface, the increase in fosterite content is negligible Fo 58.2 (±1.9) to Fo 58.9 (±0.2). At this interface, augite is only present in the oxide olivine gabbro and has a composition of En 70.4 (±0.9). The subophitic augite troctolite at the base of the section has comparable compositions of Fo 56.2 (±0.5) and En 70.1 (±1.3). A more thorough study of the cryptic mineral layering in this section is currently underway.
These textural, lithologic and mineral chemical relationships appear to be a small-scale example of the larger scale (100’s of meter) macrocyclic layering that characterizes the Cyclic Zone of the DLS (Figs. 1-3, 1-4). A pat explanation of this cyclicity may be that it represents small volume recharge events. Certainly, the mineral chemical data for one of the cumulate regression boundaries is generally consistent with this. However, this moderate shift in mineral composition may also be caused by a greater degree of trapped liquid shift in the less well foliated gabbro mesocumulate compared to the overlying troctolite adcumulate. The lack of a significant cryptic variation (and in some cases reversed cryptic shifts) at sharp cumulus regressions marking some of the cyclic layers here and at larger scale interfaces (Stops 4 & 5) led Miller and Ripley (1996) to suggest that decompression due to magma vent may be the primary process responsible for the shifts in phase equilibrium without noticeable shifts in composition. Decompression due to magma venting, although resulting in minor drops in pressure (50-150 bars), can nevertheless have pronounced effects on phase equilibrium, especially at low overall lithostatic pressures (<1.5 kb for the DLS). While the effect of decompression on solid solution mineral compositions is to promote more “primitive” compositions, the effect at very small drops in pressure is probably insignificant, even at low total pressures.

STOP 1-4: CYCLIC ZONE, DULUTH LAYERED SERIES

**Location:** North of I-35, west of Boundary Ave., slope north of Northern Engine & Supply Co. and Spirit Mtn. Red Roof Motel, Duluth. West Duluth 7.5’ quadrangle (T49N, R15W, Sec 15 SE, NAD 83 UTM - 5175100N, 559350E (area E))

**Duration:** 60 min.

**Description:** This stop examines the first macro-scale transition from troctolite cumulates to olivine gabbro cumulates that defines the base of the Cyclic Zone (Fig. 1-3). From behind the Northern Engine and Supply Co., head north and uphill to outcrops of medium-grained ophitic augite troctolite (A, Fig. 1-9). This POcf cumulate contains about 7-10% interstitial Fe-Ti oxide and augite, with the latter commonly forming 2-4 cm oikocrysts. Progressing about 70 m to the east over intermittent outcrop ledge, the augite troctolite gradually becomes coarser grained and more enriched in augite and oxide (B, Fig. 1-9).

![Figure 1-9: Outcrop geology and cryptic variation along south facing slope at Stop 1-4. Igneous foliation and layering dip at 15-25° to the east. Exposure corresponds to the top of macrocyclic unit I marking the base of the cyclic zone (Fig. 1-3). Troctolitic rocks 120 m east of the powerline behind the motel indicate the presence of an unexposed cumulus reversal.](image-url)
Crossing a 35-m gap in exposure, the next outcrop is of a medium- to very coarse grained, subophitic to ophitic olivine gabbro (PcOf; C, Fig. 1-9). In one area of the exposure, this rock type is in sharp, discordant, but unchilled contact with a coarse-grained, moderately laminated gabbroic anorthosite that is probably an inclusion of the anorthositic series. Beyond an 8-m gap is a 10-m-high outcrop knob that grades from a medium-grained, subophitic augite troctolite with 1/2-cm high density augite oikocrysts near the base (D, Fig. 1-9) to a texturally layered, medium- to fine-grained, intergranular oxide olivine gabbro at the top (E, Fig. 1-9).

Textural layering on top of knob is defined by 2- to 20-cm-thick, laterally discontinous layers of fine grained, moderately laminated, intergranular oxide olivine gabbro (microgabbro) that intermittently occurs within medium-grained, well-laminated, intergranular oxide olivine gabbro. Contacts between the medium gabbro and the microgabbro range from sharp to gradational on a scale of centimeters. In some areas, the textural layering drapes over football-sized blocks of a coarser grained, subophitic olivine gabbro, similar to the rock type seen just to the west (down section). Gossan of sulfide-bearing areas are locally present.

If time allows, we will follow flagging tape about 200 meters from the powerline (Fig. 1-9) to the parking lot behind the Red Roof motel. Exposed in an 80m-long roadcut and pavement exposure is medium-grained, well foliated, locally layered augite troctolite, thus implying that a cumulus reversal was crossed between site E and here. This rock is interpreted to form the lower part of the second macrocycle unit (Fig. 1-3). Exposure of this macrocycle boundary to the south shows that the texturally layered oxide olivine cumulate interval (E, Fig. 1-9) is only locally present and appears to be lenticular in form (Fig. 1-3). In some exposures, the boundary between macrocycle I and II is marked by a coarse-grained ophitic olivine gabbro with anorthositic series inclusions (as seen at C, Fig. 1-9) in sharp contact with troctolite.

With the exception of the medium-grained, subophitic augite troctolite at D, cryptic variations through this sequence show a general decrease in An, Fo, and En (Fig. 1-9). Plagioclase, olivine, and augite compositions in the troctolite above the layered gabbro define a regression to more primitive values. Mineral compositions are also more primitive in the microgabbro layers compared to the enclosing medium-grained gabbro. Across the cumulus reversal from oxide olivine gabbro to troctolite, Fo, En and An increase slightly.

Again a straightforward interpretation of this sequence is that it represents progressive crystallization differentiation leading to multiple saturation in plagioclase, olivine, augite, and ilmenite followed by recharge of a more primitive magma causing a regression to saturation in just plagioclase and olivine. However, the occurrence of anorthosite inclusions and the microgabbro layers suggest that any such recharge event may have been preceded by an eruption event from the chamber. Miller and Ripley (1996) interpreted the microgabbro lenses to have formed by decompression quenching of magma due its reaching water saturation in the roof zone (Miller and Ripley, 1996; see further discussion at Stops 1-5 and 1-7).

Decompression may also have triggered sulfide saturation which caused local stratiform enrichment of PGE at this and other cumulus regression. Although some enrichment in PGE above background is noted from samples taken from site E, more pronounced sulfide and PGE enrichment are evident at this macrocycle interface to the south and at the interface between the second and third macrocycles (Figs. 1-5, 1-6).
STOP 1-5: CYCLIC ZONE, DULUTH LAYERED SERIES.

Location: Roadcut on Skyline Parkway at Thompson Hill Rest Area. West Duluth 7.5' quadrangle (T49N, R15W, Sec 14, center, NAD 83 UTM - 5175350N, 560700E)

Duration: 90 min (including lunch).

Description: Before investigating this exposure as a group, we will ask each participant to sketch the mineralogic and textural attributes of the rock types observed in this roadcut. So don’t read this description until after the roadcut has been visited.

In the layered sequence of gabbroic rocks exposed along this 200-m-long roadcut (Fig. 1-10), a reversal in cumulus paragenesis can be seen that is characteristic of higher levels in the cyclic zone. The west end of the roadcut begins with a coarse-grained, moderately laminated, subophitic olivine gabbro, which locally is intergranular and elsewhere is leucocratic (sample A, Fig. 1-10). Augite in this rock is marginally cumulus but becomes definitely so quickly upsection where it consistently has an anhedral granular to subprismatic habit. This coarse-grained, intermittently layered (locally graded), olivine-poor (<5%) oxide gabbro (sample B) classifies as a PCFO cumulate. Beyond a poorly exposed interval, this gabbro includes a 2-m-thick interval wherein minor olivine becomes subpoikilitic and concentrated in layers (sample C). Another 3 m above this, the coarse gabbro passes into a medium-grained, well-laminated, subpoikilitic olivine-bearing oxide gabbro (samples D and D') which displays layering of olivine oikocryst concentration and elsewhere isomodal layers rich in Fe-Ti oxide and pyroxene. The very strong foliation and subhedral to euhedral habit of cumulus phases (plagioclase, pyroxene, and ilmenite) impart an adcumulate texture to this rock. Over a poorly exposed interval about 15 m long is an altered, coarse-grained, ophitic gabbroic anorthosite (sample E) that is texturally and mineralogically identical to rocks in the anorthositic series. At the beginning of the next well-exposed section of roadcut, several similar gabbroic anorthosite inclusions are found in a coarse-grained, subpoikilitic gabbroic anorthosite (sample F), which gradually grades upward into a more consistently subpoikilitic texture over the remainder of the roadcut (sample G). This rock type closely resembles that at the west end of the roadcut and indicates a downgrading in the cumulus status of pyroxene (and oxide?) and a reemergence of cumulus olivine.

SOUTHWEST

NORTHEAST

Figure 1-10: Geology and cryptic variation along Skyline Parkway roadcut near Thompson Hill rest area; Stop 1-5. View is to the north. Dip of lamination and layering is exaggerated; averages about 20° to the east. Contacts between units are gradational over thicknesses of 10 cm to 1 m.
The cryptic variation of En and Fo across the cumulus regression exposed in this section (Fig. 1-10) is the reverse of that expect from magma recharge. Although there is a general decrease in these parameters below the cumulus regression as would be expected due to progressive differentiation, a sharp reversal takes place at samples D and D’—the most differentiated samples based on phase mineralogy. The increase in Fo and En in these samples may reflect their adcumulate nature (i.e., low trapped-liquid component) or perhaps reflect a shift in the equilibrium compositions of mafic silicates due to the cumulus crystallization of Fe-Ti oxide. Nevertheless, the expected increase in Fo and En above the recharge horizon is not observed in either the pyroxene or the olivine. Indeed, the lowest Fo olivine in the section occurs above the cumulus regression. Again, an alternative explanation to magma recharge is that the textural and compositional variations across this interval reflect decompression of the chamber due to eruption to the surface.

Decompression of a volatile-enriched magma would cause supercooling and multiple saturation of the magma and thereby explain the abrupt decreases in grain size and cumulus phase changes without much compositional variation. Magma expulsion through the roof of the layered series would also explain the occurrence of a gabbronorite anorthosite inclusion and elsewhere throughout the cyclic zone. The hydrothermally altered nature of the gabbronorite anorthosite is consistent with a volatile-rich environment in the anorthositic series cupola of the DLS magma chamber. The cumulus reversal to ophitic olivine gabbro without an increase in mg# could be explained by repressurization of a devolatilized magma.

STOP 1-6: GABBRO ZONE, DULUTH LAYERED SERIES AND ANORTHOSITIC SERIES

Location: Roadcuts on Skyline Parkway above Oneota Cemetery. Duluth Heights 7.5’ quadrangle (T49N, R15W, Sec 1, SE, approx. NAD 83 UTM - 5177970N, 562995E)

Duration: 30 min.

Description: In roadcuts along a 0.5-km section of Skyline Parkway, rocks forming the contact between the layered series and the anorthositic series may be examined. Exposed in low, deeply weathered outcrops at the west end of the section is a poorly to well foliated, intergranular, apatitic olivine ferrodiorite cumulate (PCFOA). It is composed mostly of plagioclase (zoned An38-50; avg. An44), augite (avg En33Fs27Wo40), and bladed ilmenite. In addition, as much as 10% olivine (Fo30), 5% orthopyroxene (En45), 5% apatite, 3% biotite, and 5% granophyric mesostasis is present. Generally medium-grained, it locally varies in grain size from fine to coarse. Medium- to fine-grained variants have well-developed foliation, whereas coarser grained ferrodiorite tends to be poorly foliated to nonfoliated. Coarser ferrodiorite tends to be more granophyric, as well. By being locally well-laminated, olivine-bearing, and lacking ferromonzodioritic component, the ferrogabbro here is not typical of the upper contact zone of the layered series; relationships more characteristic of the upper contact zone will be seen at the next stop. Rather, this rock is more typical of gabbroic cumulates of the gabbro zone.

About 35 meters east of the ferrogabbro, a prominent roadcut displays several common variants of anorthositic rocks that compose the anorthositic series. The western end of the roadcut is composed of a poorly to moderately laminated, poikilitic olivine gabbroic anorthosite (OGA) that contains olivine (Fo30-46) oikocrysts up to 6 cm across, as well as interstitial augite and oxide. Progressively eastward, this rock type grades into a subpoikilitic to granular olivine gabbronorite anorthosite. At the high point in the roadcut, this granular OGA contains an inclusion of olivine (Fo60)-bearing anorthosite (Photo 1-5). Whereas the enclosing OGA contain about 80-85% plagioclase (avg. An65), this inclusion contains more than 95% plagioclase (unzoned An65). The contact between OGA and the anorthosite inclusion is sharp with some discordant alignment of plagioclase in OGA.
The inclusion relationships and the outcrop-scale variability in internal structure and lithology (mode, texture, olivine habit, and lamination development) of the anorthositic rocks here are ubiquitous features of the anorthositic series. These complexities led Taylor (1964) to characterize the anorthositic series as an igneous breccia. He and later Miller and Weiblen (1990) concluded that these rocks formed by repeated intrusions of plagioclase crystal mush.

This stop is at the western end of a westward projection of the layered series-anorthositic series contact (Fig. 1-2). A possible explanation for the irregular trace of the contact is that it reflects the original shape of the DLS roof. This would seem to be a difficult shape to maintain if the anorthositic series rocks were hot and lighter than the DLS magma. Rather, it seems more likely that the westward projection of the anorthositic series represents a large inclusion that detached from the roof zone and settled down to the cumulate floor of the DLS at the time of gabbro zone crystallization. Evidence for this is suggested by a truncated cryptic variation in the DLS leading up to this contact compared to the thicker DLS section to the north and the atypical character of the ferrodiorite in contact with the anorthositic series here (compare with next stop).

STOP 1-7: DLS “CHILL”, GRANOPHYRE, AND ANORTHOSITIC SERIES

Location: Skyline Parkway, Duluth Heights 7.5’ quadrangle (T50N, R14W, Sec 32, SE, NAD 83 UTM - 5179675N, 564880E).

Duration: 30 min.

Description: Exposed at the northeast end of this roadcut is a fine-grained mafic rock with intermingled granophyre that together cut coarse-grained olivine gabbroic anorthosite of the anorthositic series. Since early mapping by Grout in the Duluth area in 1912, this rather innocuous exposure has been a keystone outcrop in interpreting the intrusive history of the Duluth Complex. This fine-grained mafic rock can be traced up over the ridge to the west where it merges into the upper contact zone of Layered Series. Grout (1918a) and later Taylor (1964) saw this exposure as evidence that the anorthositic series was considerably older and cold when the layered series was intruded. This paradigm was accepted by all subsequent workers on the Duluth Complex up through the 1980’s. It came therefore as a shock when high resolution U-Pb age dating (Paces and Miller, 1993) showed that the anorthositic series and the layered series were virtually identical in age (within 0.5 Ma.
relative to the 22 Ma span of Midcontinent Rift magmatic activity). This precipitated a major paradigm shift in the perception of the intrusive relationships between these two series here and throughout the Duluth Complex.

A closer look at this DLS “chill” reveals that it is not a thermal quench of the Layered Series at all. This rock type is found at the contact with the anorthositic series throughout most this area and has a remarkably homogeneous composition with an mg# of about 37 (Table 1-1). In thin section, it is a subprismatic biotitic oxide ferrodiorite. Applying its composition to the MELTS routine indicates that it should be in equilibrium with augite, ilmenite, and plagioclase with compositions comparable to gabbroic cumulates found in the cyclic zone and gabbro zones of the DLS. In sum, this rock is much too evolved to have produced the troctolitic rocks of the layered series. Rather than this being a thermal quench, Miller and Ripley (1996) have interpreted this rock to represent decompression quenching of an evolved, water-saturated DLS magma during venting at a time when the cyclic zone was crystallizing. Whereas decompression of a water-undersaturated magma should result in superheating and a suspension of crystallization (or at least a significant change in phase equilibrium), decompression under water-saturated conditions should cause supercooling and quenching. This model is fits nicely with the explanation for the cyclic zone with which this composition is apparently comagmatic.

The lobate contacts between the irregular masses of medium-grained granophyre and the fine-grained ferrodiorite host (Photo 1-6) give the appearance of two magma mixing. The ferrodiorite is not of a composition that would indicate that these two liquid formed by immiscibility. An alternative explanation is that these felsic magmas were derived from anatectic melting of various inclusion carried into the DLS chamber. Because of their high silica content and low density, these felsic melts did not readily mix or assimilate with mafic melt, but rather rose to the roof zone where they ponded beneath the anorthositic series cupola. During magma venting from the chamber, the felsic melts became entrained and irregularly mixed with the mafic magmas. While decompression under water-saturated conditions caused rapid crystallization of the mafic magma, the felsic melt became irregularly entrapped in the quenched mafic host and cooled more slowly to a medium-grained texture.

Photo 1-6. Lobate contacts between fine-grained oxide ferrodiorite (fd) and medium-grained melanogranophyre (mg), which is in sharp contact with coarse-grained gabbroic anorthosite (ga) at Stop 1-7.
Table 1-1. Compositions of six fine-grained ferrodiorite samples collected at the DLS-AS contact.

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(Analyses by ActLab, Ancaster, Ontario; Miller unpublished data)

STOP 1-8: FERRODIEROTIE/MELANOGROANOPHYRE COMPOSITE INTRUSION IN ANORTHOSITIC SERIES

Location: Roadcuts on Skyline Parkway on the south and north sides of Twin Ponds swimming area. Duluth 7.5' quadrangle (T50N, R14W, Sec 21, E central; NAD 83 UTM - 5180870N, 566980E).

Duration: 60 min.

Description: Outcrops and roadcuts north and south of Twin Ponds expose contact relationships between very altered anorthositic series rocks and an irregular composite body of intermediate to felsic rocks. Exposed in the roadcut south of the T-junction is an altered, coarse-grained, granophyric gabbroic anorthosite. All ophitic pyroxene has been replaced by fibrous amphibole, and a granophyric mesostasis locally composes 5-15% of the rock. The altered and granophyre-enriched character of anorthositic rocks is common over most of the upper part of the anorthositic series in the Duluth area (Fig. 1-1).
About 15 m east of the T-junction, an abrupt but unchilled contact is exposed between the gabbroic anorthosite and a medium-grained, apatitic olivine ferromonzodiorite. As seen in thin section, all the olivine and most of the clinopyroxene has been replaced by amphibole, chlorite, and iron oxide, and plagioclase is commonly mantled by dusty K-feldspar which becomes intergrown with quartz to form a granophytic mesostasis. Locally the ferromonzodiorite is moderately laminated, and in one area it displays a streaky modal layering that is moderately inclined to the southeast. About 75 m east of the junction, a very complex contact between the ferromonzodiorite and a plagioclase-porphyritic quartz ferromonzodiorite is encountered which appears to be a hybrid mixture of gabbroic anorthosite and ferromonzodiorite. Over a 25 m interval, this hybrid rock grades into variably altered and granophytic gabbroic anorthosite. With the exception of small irregular bodies of quartz monzodiorite about 140 m from the junction, the remainder of the roadcut is altered and granophytic gabbroic anorthosite.

On the north side of the Twin Ponds, a roadcut exposes a pink, mafic quartz monzonite (or melanogranophyre) cut by a 2-m-wide tholeiitic diabase dike. The melanogranophyre is composed of about 50% subhedral plagioclase, 5-10% skeletal prisms of Fe-pyroxene and amphibole, and 5% granular Fe-oxide in a felsic matrix of micrographically intergrown dusty K-feldspar and quartz. This rock type makes up 80% of the irregular composite body which is labelled as melanogranophyre in Figure 1-1. Uphill (north) from the roadcut in intermittent pavement outcrops, the melanogranophyre can be observed to grade into more mafic compositions (quartz ferromonzodiorite to ferrodiorite) as sharp but unchilled contacts with gabbroic anorthosite are approached.

The alteration, contact relationships, and variety of rock types observed here indicate that evolved magma and hydrothermal fluids emanating from the underlying DLS passed through the anorthositic series over a protracted period of time and at a variety of scales. The very altered and granophyre-rich character of anorthositic rocks observed here and over much of the upper part of the anorthositic series suggests that late-stage melts and hydrothermal fluids fluxed through the intercumulus pore spaces of the (partially molten?) anorthositic series over a large area. In addition to this widespread percolation, the composite melanogranophyre body appears to represent a discrete conduit through which DLS-originating magmas passed and partially crystallized on their way to higher level intrusions or surface eruptions. The crude zonal distribution of composition more ferrodioritic at the margins and more quartz monzonitic in the interior—is consistent with this conduit being open during crystallization of at least the upper third of the DLS. Moreover, the hybridization between the composite body and the gabbroic anorthosite host suggest that the anorthositic series was partially molten at least in the vicinity of this conduit.

STOP 1-9: UPPER CONTACT OF DULUTH COMPLEX AND NORTH SHORE VOLCANIC GROUP.

Location: Radio Tower Hill. East of corner on gravel road corresponding to 5th Ave and 9th Street. Duluth 7.5' quadrangle (T50N, R14W, Sec 28, NE; NAD 83 UTM - 5182260N, 567650E).

Duration: 45 min.

Description: The east side of Radio Tower Hill overlooking downtown Duluth approximates the slope of the upper contact of the Duluth Complex with the overlying lava flows of the North Shore Volcanic Group, which now underlie all the lower ground to the northeast along the shore. As observed at the southeastern crest of the hill, the rock exposed over most of this slope is a medium- to fine-grained, plagioclase-porphyritic (5-15%), subophitic to ophitic olivine gabbro that contains many decimeter- to meter-sized basaltic hornfels inclusions. In thin section, the gabbro typically displays intense hydrothermal alteration...
resulting in sericitic breakdown of plagioclase and uralitic, chloritic, and oxide replacement of pyroxene and olivine, though its primary subophitic to ophitic texture is typically preserved. The basaltic inclusions are locally intensely recrystallized and the gabbro shows little to only a weak chill around the inclusions. Less commonly, an inclusion of gabbroic anorthosite is present in the gabbro. To the west (downsection), basaltic inclusions become less common and plagioclase phenocrysts become more abundant, but in a nonsystematic way. The contact with the main suite of gabbroic anorthosite is not well exposed but seems to be abrupt and may actually finger into the anorthositic series as dike-like apophyses (Fig. 1-11).

Along a telephone line down the slope to the northeast, the gabbro gradually becomes finer grained and less porphyritic. At the base of the slope, the gabbro abruptly grades into a pink, medium-grained, intergranular to micrographic hornblende quartz monzonite (Fig. 1-11). The quartz monzonite is composed of ~15% amphibole and ferroaugite, 5% granular Fe-oxide, 40% plagioclase, 30% dusty K-feldspar, and 10% graphic to granular quartz. Abundant miarolitic cavities indicate a shallow depth of crystallization. The contact relationship between the gabbro and the quartz monzonite is best seen in a roadcut along the driveway to 415 W. Skyline Parkway. Here, the two phases, along

![Figure 1-11: Outcrop geology of Radio Tower hill area, showing the starting and ending locations of Stop 1-9. Open circles indicate the location of radio towers.](image)

with some basaltic inclusions, occur in a complex mixture over a 15-m-wide zone. The melanogranophyre probably formed by partial melting of intermediate to felsic lavas of the overlying North Shore Volcanic Group which form the hanging wall of the Duluth Complex. A strongly recrystallized porphyritic felsic (icelandite) volcanic rock can be observed in low roadcuts about 40 m northeast of Skyline Parkway on W. 8th St.

A possible interpretation of the porphyritic gabbro is that it represents the upper border phase of the anorthositic series that formed by flow differentiation of plagioclase crystals away from the contact with overlying volcanic rocks. An alternative explanation is that this body represents a discrete intrusion, perhaps comagmatic with the layered series, which was emplaced at the anorthositic series-volcanic contact. Except for its highly altered state, its primary mineral compositions and texture are similar to the basal contact zone rocks of the layered series.
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Severson, M.J., 1995, Geology of the southern portion of the Duluth Complex: Natural Resources Research Institute, University of Minnesota-Duluth, Technical Report NRRI/TR 95/26, 185p. (with plates)


