ALASKAN-TYPE ULTRAMAFIC ROCKS IN BRITISH COLUMBIA: NEW CONCEPTS OF THE STRUCTURE OF THE TULAMEEN COMPLEX*

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INTRODUCTION

Alaskan-type ultramafic rocks in British Columbia are potential hosts for commercially exploitable deposits of platinum metals (Rublee, 1986; Evenchick *et al.*, 1986) as well as other commodities (for example, chrome, nickel, cobalt, asbestos and jade). In 1987 the British Columbia Geological Survey initiated a program designed to investigate the mineral potential of these intrusions through detailed geologic mapping and lithogeochemical sampling specifically for platinum group elements. In the first year of this project, a concerted effort is being made to more thoroughly understand one of these intrusions, the Tulameen ultramafic complex in southern British Columbia. The Tulameen complex warrants careful attention as it has been the largest producer of platinum in the province and has been taken as a typical example of a zoned Alaskan-type ultramafic intrusion (Findlay, 1963, 1969; Evenchick *et al.*, 1986).

The general structure of Alaskan-type complexes is characterized by a crudely concentric outward zonation of rock types ranging from olivine-bearing to hornblende-rich or magnetite-rich clinopyroxenites about a steeply dipping dunite core (Taylor, 1967). Lesser proportions of hornblendite and mafic pegmatite usually occur as isolated masses toward the periphery of the intrusion. Typical cumulate minerals include forsteritic olivine, diopsidic augite, chromite and magnetite; orthopyroxene is characteristically absent, indicating an alkalic affinity. Gabbroic rocks associated with the intrusion are commonly tholeiitic, and in this respect the syenogabbros and syenodiorites of the Tulameen complex are unusual (Findlay, 1969).

This report summarizes the results of geological fieldwork in the Tulameen conducted between July 1 and September 4, 1987. Our study brings out the intense deformation and structural complexity of the ultramafic complex and its host rocks; questions the mechanism of emplacement and igneous zonation previously proposed to account for the crudely concentric outcrop pattern of principal rock types; and provides evidence for mechanisms of emplacement of cumulate sequences that tend to obliterate primary layering. The structure of the complex is particularly important in further testing the potential for economic concentrations of platinum. Subsequent work will focus on a number of other Alaskan-type intrusions in northern British Columbia. The ultramafic program is funded by the Mineral Development Agreement between Canada and the Province of British Columbia, and by a British Columbia Geoscience Research Grant awarded to the junior author to defray field expenses incurred as part of Master's thesis work at Ottawa University.

LOCATION AND ACCESS

The Tulameen ultramafic complex underlies 60 square kilometres of rugged forested terrain centred 23 kilometres due west of Princeton (Figure 2-2-1). Physiographically, the region lies in a transition zone between the Cascade Mountains to the west and the Interior Plateau to the east. The project area is covered by map sheets 92H/07 and 92H/10 at a scale of 1:50 000. Paved highway connects Princeton with the communities of Coalmont and Tulameen where a network of well-maintained logging roads leads westwards into the intrusion. The Tulameen River road provides access to a complete cross-section through the intrusion, intersecting the dunite "core" approximately 10 kilometres west of the village of Tulameen.

GEOLOGIC SETTING

The Tulameen ultramafic complex is situated within the southwestern Intermontane Belt immediately west of the juncture of the Quesnellia tectonostratigraphic terrane and Mount Lytton plutonic complex (Figure 2-2-1). The project area lies within a zone of Early Tertiary "transtensional" block faulting related to regional right-lateral transform motions along the Fraser River–Straight Creek fault system (Ewing, 1980; Monger, 1985).

The general geology of the Tulameen complex is shown in Figure 2-2-2. The intrusive suite was emplaced into metasedimentary and intermediate to felsic metavolcanic lithologies that belong mainly to the western facies of the Upper Triassic (Carnian to Lower Norian) Nicola Group (Preto, 1975, 1979; Price *et al.*, 1987). Volcanic assemblages in the Nicola Group contain clinopyroxene-rich shoshonitic lavas that evolved during Late Triassic subduction (Mortimer, 1986). These rocks are possibly comagmatic with ultramafic and mafic alkalic rocks of the Tulameen suite (Findlay, 1969). The Tulameen complex and its host rocks are

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unconformably overlain by terrigenous sedimentary and volcanic assemblages of the Early Tertiary (Eocene) Princeton Group and Miocene plateau basalts.

Regional structures trend approximately north-northwest and are characterized by a westward-dipping foliation that parallels the eastern margin of, and extends into, the southern extension of the Mount Lytton batholith, otherwise known as the Eagle plutonic complex. The Tulameen complex forms an elongate body concordant with the structural grain.

Previously published potassium-argon dates for the Tulameen complex yield a preferred estimate of 175 Ma (mid-Jurassic), but this may be too young due to subsequent loss of radiogenic argon during metamorphism (Roddick and Farrar, 1971, 1972). Published potassium-argon dates for the Eagle

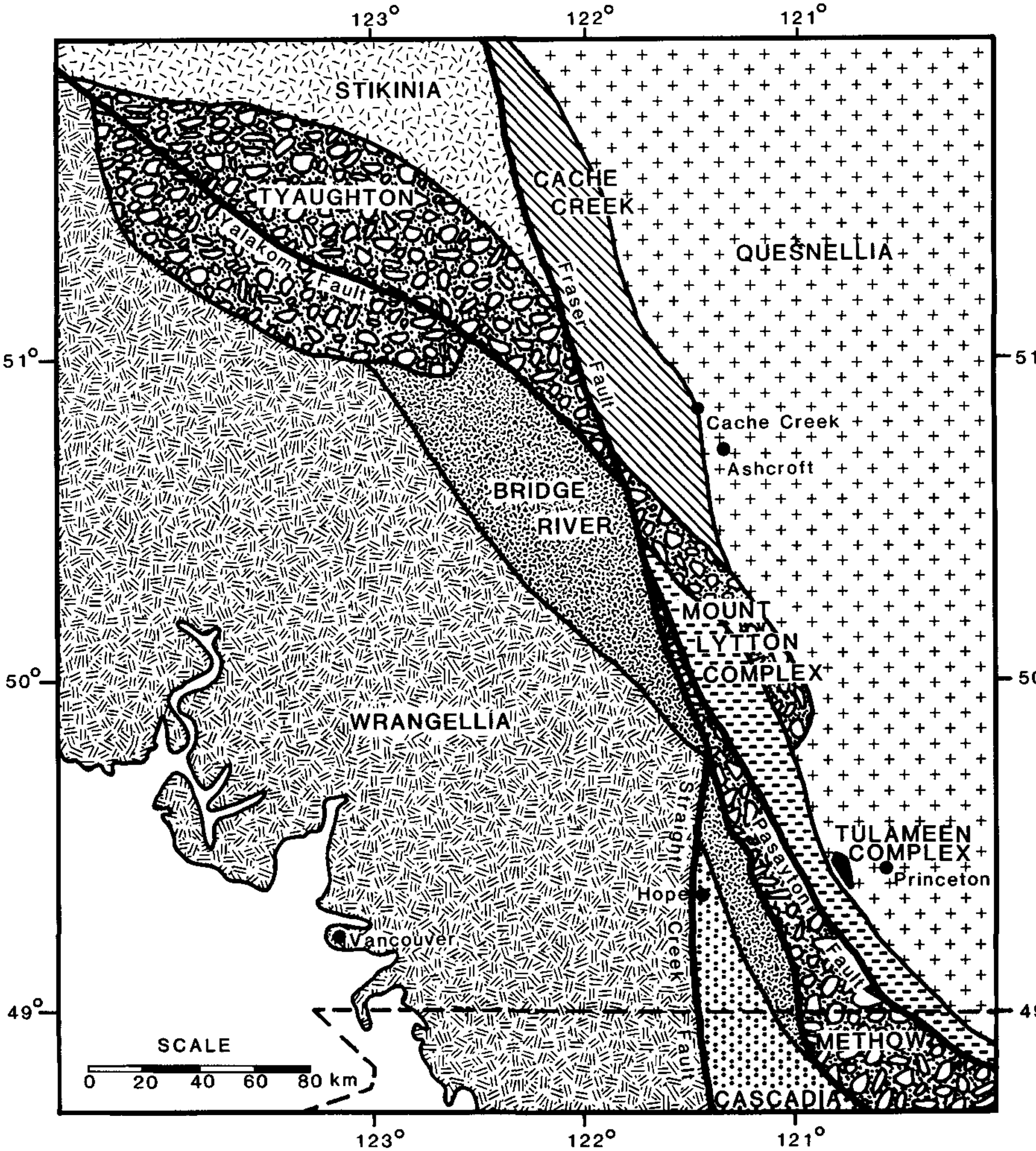

Figure 2-2-1. Geologic setting of the Tulameen ultramafic complex in relation to tectonostratigraphic terranes (modified after Kleinspehn, 1985).

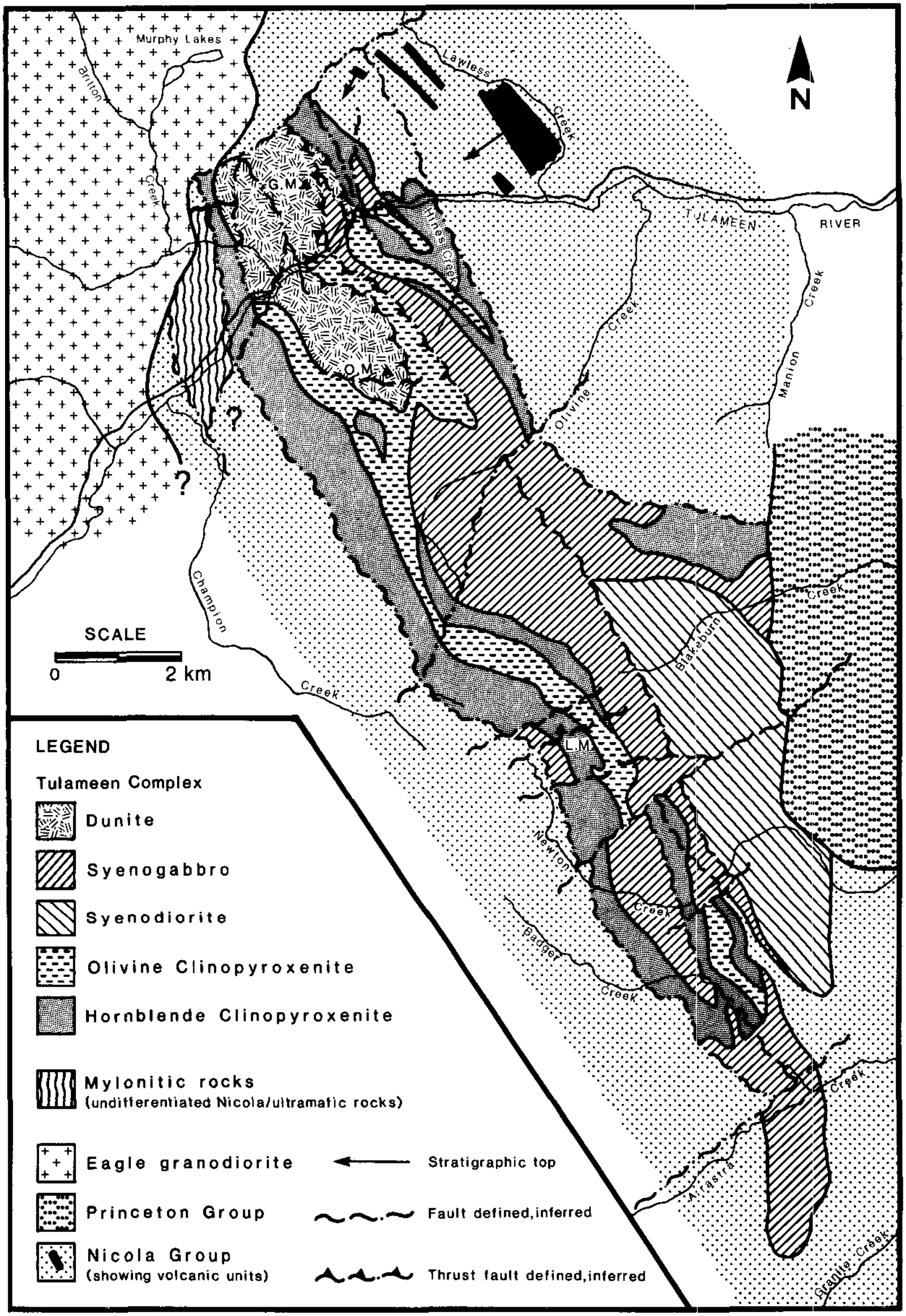

Figure 2-2-2. Generalized geologic map of the Tulameen ultramafic complex (modified after Findlay, 1963).

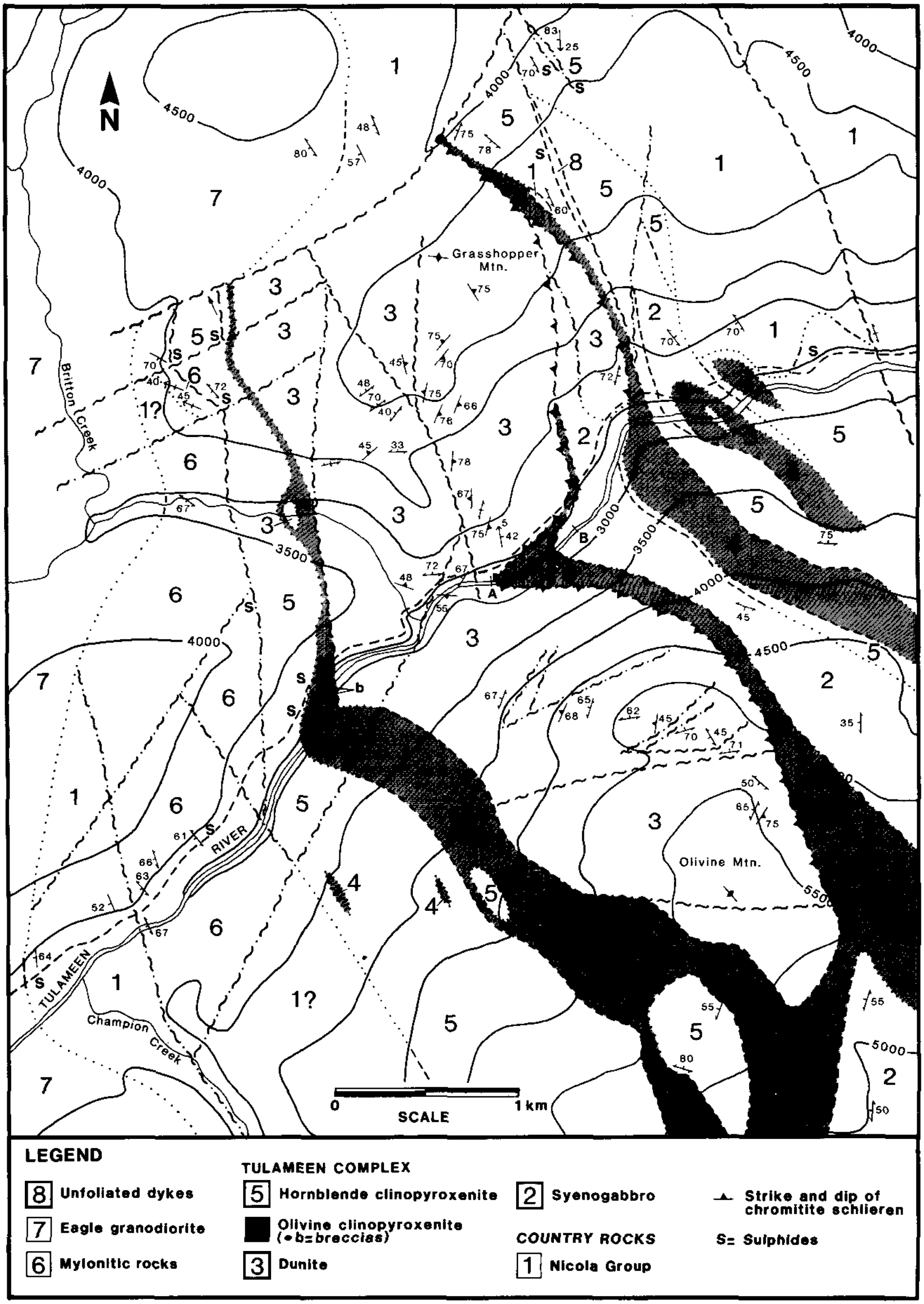

Figure 2-2-3. Detailed geologic map of the northern part of the Tulameen ultramafic complex (modified after Findlay, 1963). A-B refers to the location of the measured stratigraphic section (Figure 2-2-4).

pluton (Roddick and Farrar, 1972) and preliminary results of ongoing potassium-argon, rubidium-strontium, and uranium-lead geochronometry, suggest a probable Early to mid-Cretaceous (97 to 120 Ma) age of emplacement (C. Greig, personal communication, 1987).

COUNTRY ROCKS

NICOLA GROUP

Representatives of the Nicola Group in the Tulameen region comprise black thinly laminated argillites, green and brown tuffaceous siltstones and lapilli tuffs, dark grey-green aphyric to plagioclase-phyric pyroxene andesite and hornblende dacite flows, rare aphanitic rhyolites, cherts, chert breccias, and dark grey limestones. All lithologies are regionally metamorphosed to greenschist grade. Chlorite-muscovite schists with minor biotite are common to the west of the ultramafic complex and marbles with weakly developed skarns commonly occur adjacent to the Eagle granodiorite contact. Skarn mineralization includes traces of molybdenite, chalcopyrite, pyrite, covellite, bornite and chalcocite (?).

Beyond the northeastern margin of the intrusion, andesitic lavas preserve primary flowage features such as vesicle trains aligned within the flow foliation, chilled basal zones overlying baked sedimentary horizons, and basal flow breccias caught in "squeeze-ups". The latter two criteria indicate that these lavas are the right way up (Figure 2-2-2). A distinctive variety of porphyritic flow contains large (<4 centimetres) feldspar laths with subtrachytic texture previously referred to as "bladed feldspar porphyries" (Preto, 1975, 1979).

PRINCETON GROUP

The Princeton Group contains sub-greenschist grade lithologies of Tertiary (Eocene) age that have been deformed and rotated by block faulting (Ewing, 1980; Monger, 1985). Rock types include thinly bedded coal seams and seat earths, fissile shales yielding plant remains, arkosic sandstones and conglomerates, polymictic laharic breccias, biotite rhyolite, hornblende-phyric dacite, and locally pillowed olivine basalt flows and hyaloclastites. The Princeton Group is locally capped by subhorizontal amygdaloidal basalts of Miocene age that are unfaulted (Monger, 1985).

EAGLE GRANODIORITE

The Eagle pluton comprises a foliated to gneissic (syntectonic) granodiorite and variably deformed (syntectonic to post-tectonic) muscovite granite. Granodiorite at the western margin of the study area is a medium to coarse-grained rock containing quartz, plagioclase, potassium feldspar and biotite. The granodiorite is weakly to intensely foliated, cut by quartz veins and locally encloses amphibolitic schlieren. Near the contact with the Nicola on the Tulameen River road, numerous aplite sills (<1 metre) that are generally concordant with westward-dipping argillites and metasiltstones are probably rooted in the Eagle pluton. On Britton Creek, unfoliated biotite-hornblende granodiorite contains randomly oriented xenoliths of amphibole-biotite-chlorite schist derived from adjacent mylonitic rocks. Recent mapping has identified this granitoid stock as a post-tectonic intrusion of probable Tertiary (Eocene ?) age (C. Greig, personal communication, 1987).

TULAMEEN ULTRAMAFIC COMPLEX

Comprehensive reports of the geology and economic mineral occurrences in the Tulameen district are provided by Camsell (1913) and Rice (1947). However, the most complete accounts of the geology and petrology of the ultramafic complex are provided by Findlay (1963, 1969). The distribution of mappable units observed during the field season is as determined by Findlay (1963). However, we have a somewhat different view of relationships among some of the major rock units and structural evolution of the complex. The principal ultramafic-mafic units comprise dunite, olivine clinopyroxenite, hornblende clinopyroxenite and gabbroic rocks (Figures 2-2-2, 2-2-3).

ULTRAMAFIC ROCKS

DUNITE AND CHROMITITE

Outcrops of dunite are restricted to the northern part of the complex at Grasshopper and Olivine mountains. The dunite is medium to dark grey where fresh, buff weathering and well jointed. The primary mineralogy consists of forsteritic olivine, accessory chromite and rare diopsidic augite. Alteration products include serpentine, carbonate, magnetite and talc. In general, the degree of serpentinization decreases from east (80 volume per cent serpentine) to west (20 per cent) where the lowest loss-on-ignition values (<2 weight per cent volatiles) are recorded (Findlay, 1963; White, 1987).

Concentrations of chrome spinel and massive chromitite appear to be distributed randomly throughout the dunite as discrete layers, nodular masses and schlieren up to 1 metre in length and 6 centimetres in width. Chromitite schlieren are commonly distinguished in outcrop by a pale alteration halo (0.1 to 1 centimetre). Associated with the chromite are microscopic grains of platinum minerals (for example, platinum-iron alloy, sperrylite), nickel-iron sulphides (for example, pentlandite, violarite, bravoite), chalcopyrite and pyrite (St. Louis *et al.*, 1986).

OLIVINE CLINOPYROXENITE

The principal outcrops of olivine clinopyroxenite envelop the dunite "core" and extend southwards along the central part of the complex. In addition, three discrete bodies of olivine clinopyroxenite that are distinctly elongate along the regional structural trend occur in the northeastern part of the intrusion. The fresh rock is medium to coarse grained and has a blotchy green and black appearance due to partially serpentinized olivine (<20 per cent serpentine) and deep green clinopyroxene. Sporadic pegmatitic masses contain crystals up to 8 centimetres across and olivine segregations locally form schlieren.

Breccias

Breccias within the olivine clinopyroxenite unit are well exposed in the banks of the Tulameen River near the western

Plate 2-2-1. Angular block of layered dunite (Du) – pyroxenite (Px) in sulphide-rich serpentinized breccia within westernmost olivine clinopyroxenite unit exposed in the Tulameen River.

margin of the dunite (Figure 2-2-3). Angular to rounded blocks (<0.5 metre) of dunite, pyroxenite and interlayered dunite-pyroxenite (Plate 2-2-1) are enclosed in a serpentinized pyroxene-rich matrix carrying calcite and disseminated sulphides (largely pyrite). On the eastern bank, the southern margin of a similar breccia is in contact with a body of dunite 8 metres thick which is succeeded southward by another breccia with clasts that are predominantly foliated (mylonitized ?) gabbro in random orientation. All observed contacts between breccias and host pyroxenite dip moderately to steeply (30 to 70 degrees) south. The cause of brecciation is not presently clear and may involve either tectonic or localized explosive activity.

Hornblende Clinopyroxenite

Hornblende clinopyroxenite generally occurs at the periphery of the complex. This unit is continuous along the western margin of the intrusion but is more irregularly distributed to the east. The fresh rock is medium to coarse grained and contains diopsidic augite, hornblende, relatively abundant magnetite, and minor biotite, apatite and disseminated sulphides; feldspathic variants are extremely rare. Medium-grained varieties commonly exhibit mineral foliations and/or hornblende lineations. Biotite locally forms coarse books (1 centimetre) and amphiboles commonly reach 1 to 3 centimetres in size. Accessory biotite and apatite are reported to occur in 6-metre-thick magnetite-rich layers that are poorly exposed in old workings on the southern slopes of Tanglewood Hill (Eastwood, 1959). Massive magnetite is also found as schlieren and podiform masses on Lodestone Mountain and is commonly associated with coarse-grained hornblende and clinopyroxene segregations. This rude igneous layering generally parallels mineral foliations developed in this region.

Minor Ultramafic Rocks

Rock types that are generally not mappable units include peridotite, clinopyroxenite, hornblende-olivine clinopyroxenite, hornblendite, "hybrid" rocks and mafic pegmatite. The latter rock exhibits large (6-centimetre) hornblende crystals with interstitial feldspar and usually passes gradationally into finer grained hornblendite. Mafic pegmatites are preferentially distributed near the margins of hornblende clinopyroxenite bodies (Findlay, 1963). "Hybrid" rocks are characterized by gabbroic xenoliths in various states of assimilation and generally occur at gabbro contacts (Findlay, *ibid.*). However, gabbroic xenoliths are also found at the summit of Lodestone Mountain.

GABBROIC ROCKS

The gabbroic rocks (or simply "gabbros") were subdivided by Findlay (1963) into syenogabbro and syenodiorite. Findlay's nomenclature is retained in this preliminary report but these rocks might equally have been named diorite, monzonite, or variants thereof, depending on the classification system used.

The main mass of gabbroic rocks is distributed eccentrically on the eastern side of the complex. In the north, gabbros are commonly in direct contact with olivine clinopyroxenite but only rarely lie against dunite. In the south, well-foliated and/or strongly lineated fine to medium-grained gabbroic rocks extend southwards across Arrastra Creek but their southern limit is poorly defined. These rocks were formerly mapped as "Badger gneiss" by Findlay (1963) who considered them to be contact-metamorphosed equivalents of the Nicola Group. The syenodiorite is confined to the southeastern margin of the intrusion where it is unconformably overlain by the Princeton Group.

Essential minerals are plagioclase (andesine), clinopyroxene, hornblende and potassium feldspar with minor biotite and opaques and accessory apatite and sphene. Syenodiorite is more leucocratic than syenogabbro and contains slightly less calcic plagioclase (Findlay, 1963, 1969). Textures range from equigranular to foliated and some rocks exhibit strong mineral elongation. Most gabbroic rocks are extensively saussuritized and appear various shades of green; fresh rocks are pale to medium grey or pinkish grey, depending on the nature and proportion of the feldspar. Sulphide-rich hornblende-bearing gabbros (described below) occur as thin units within olivine clinopyroxenite in the Tulameen river bed.

MAGMATIC STRATIGRAPHY: TULAMEEN RIVER SECTION

An almost continuous stratigraphic section (530 metres) along the Tulameen River, beginning at the eastern margin of the dunite and passing through olivine clinopyroxenite into the gabbroic rocks, is presented in Figure 2-2-4. The section is cut by unfoliated hornblende-bearing dacitic and basaltic dykes, probable feeders for Tertiary lavas in the Princeton Group and Miocene basalts, and contains major tectonic breaks at the dunite-pyroxenite and pyroxenite-gabbro contacts. Two thin gabbro units are also well exposed within the pyroxenite.

Olivine Clinopyroxenite

The olivine clinopyroxenite unit is rather massive and characterized by abundant xenoliths of dunite ranging in size

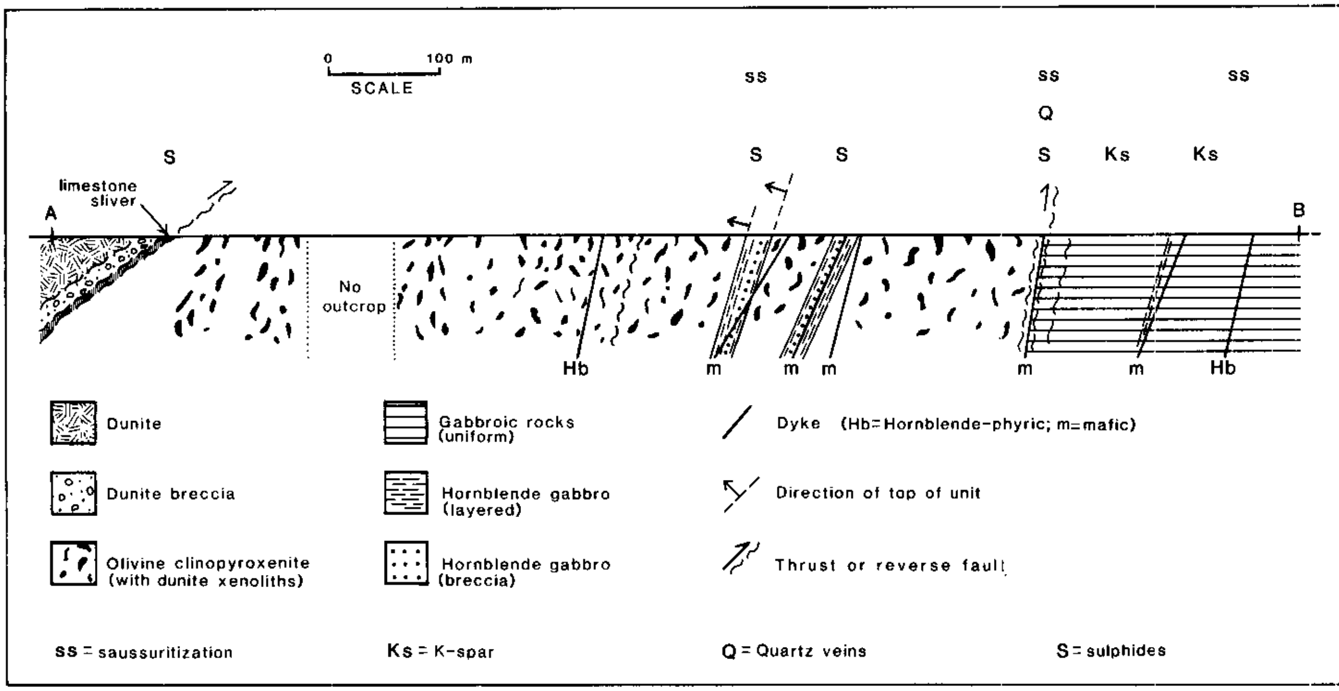

Figure 2-2-4. Stratigraphic section along the Tulameen River bed at the eastern margin of the dunite (*see* Figure 2-2-3 for location).

from a few centimetres to 10 metres or more. Xenoliths locally exhibit clinopyroxene megacrysts or crystal clots, and the larger bodies of dunite may enclose pyroxenite xenoliths that appear to have been derived from their host. Xenolith shapes are diverse: round, wispy, tabular, or distinctly elongate and contorted; and contacts with their pyroxenite host are planar to irregular or crenulate (Plate 2-2-2). Rarely, dunite and pyroxenite are interlayered and appear to have behaved as cohesive blocks within the unit. However, the majority of xenoliths preserve features that suggest that they were deformed while hot and still capable of plastic deformation. The origin of these textures is related to episodic slumping of dunite-pyroxenite layered cumulates deposited elsewhere in the intrusion and emplaced at their present location by mass flowage down the cumulate slope.

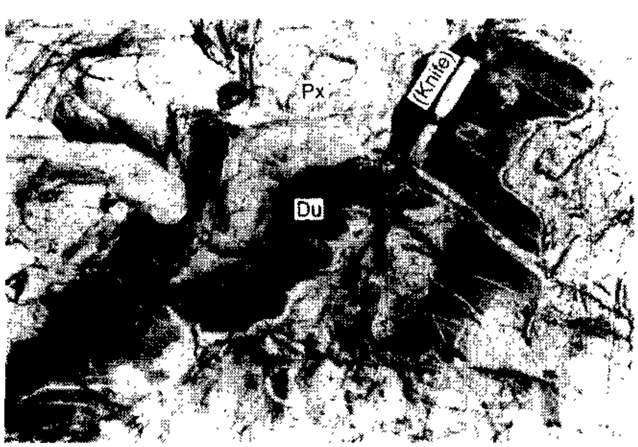

Plate 2-2-2. Intricately contorted ribbon-shaped xenolith of dunite (Du) in olivine clinopyroxenite (Px), Tulameen River section. Veins of carbonate and serpentine cut both xenolith and host.

Gabbros

Hornblende-bearing gabbro units within the olivine clinopyroxenite each contain three medium-grained subunits comprising a lower and upper layered sequence separated by gabbro breccia. Contacts with the olivine clinopyroxenite are sharp and depositional. The layered gabbros preserve a wealth of sedimentary features, including modal grading of plagioclase and ferromagnesian phenocrysts in which the density grading may be normal or reverse in different layers (Plate 2-2-3); and erosional unconformities which transect earlier layers (Plate 2-2-4). The latter features consistently indicate that stratigraphic tops face west toward the dunite

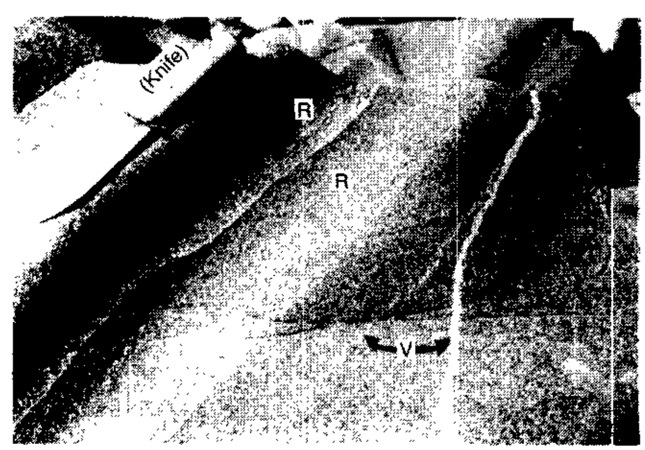

Plate 2-2-3. Reverse modal grading (R) of plagioclase and ferromagnesian cumulate crystals in layered gabbro within olivine clinopyroxenite, Tulameen River section. Leucogabbro segregation veinlets (V) are injected parallel to and across the layering.

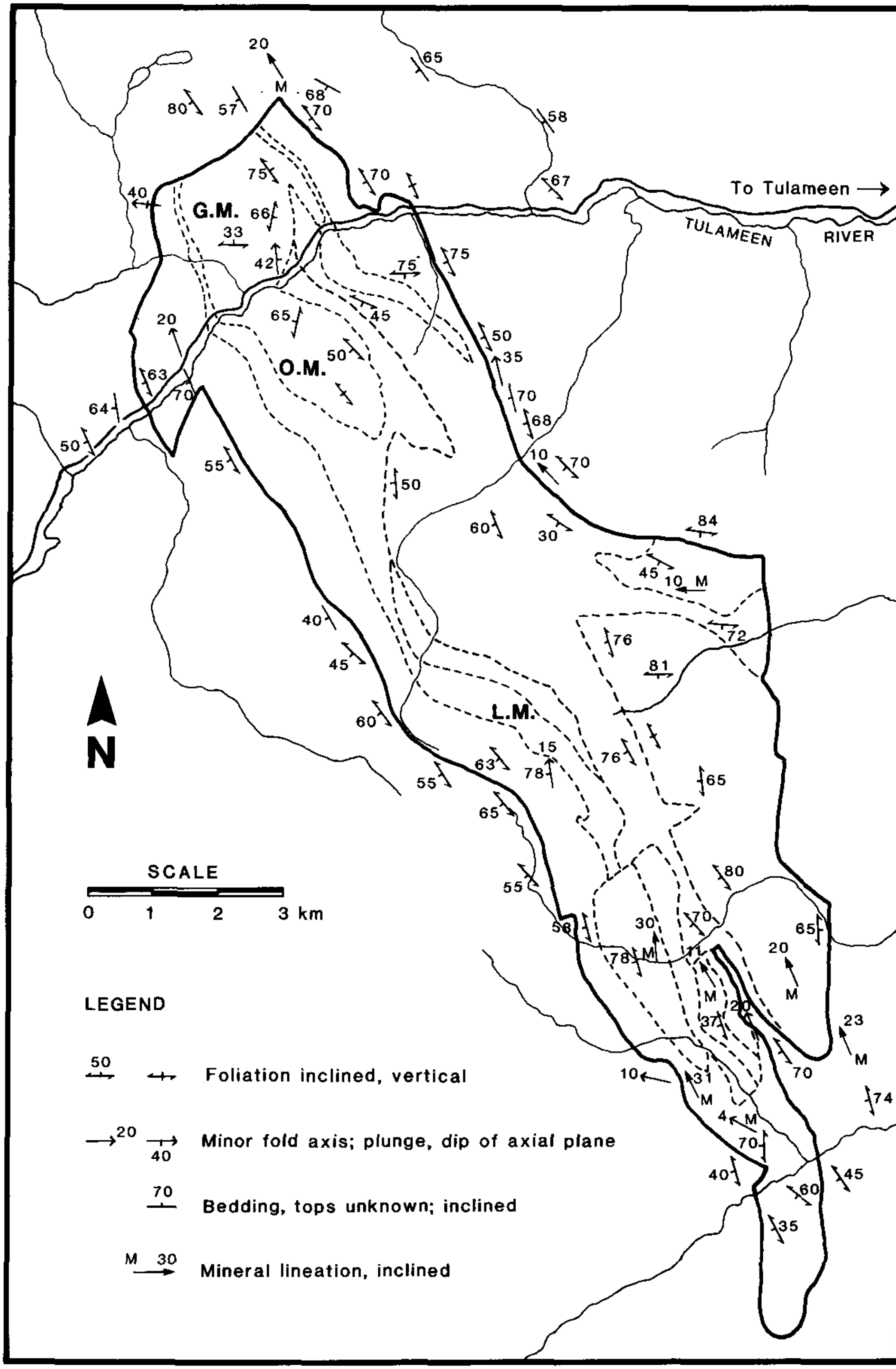

Figure 2-2-5. Representative measurements of structural fabrics in the Nicola Group and Tulameen ultramafic complex.

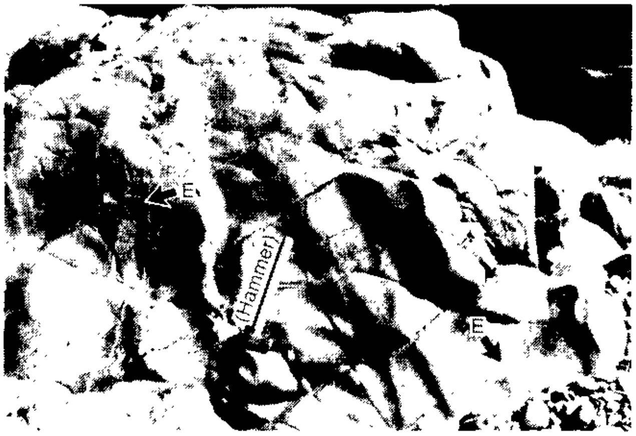

Plate 2-2-4. Layered hornblende-bearing gabbros, Tulameen River section. Note erosional truncation of layering (E) indicating stratigraphic tops face right (upstream).

Plate 2-2-5. Segregation vein (V) of leucogabbro cutting base of layered gabbro (G), underlying olivine clinopyroxenite unit (Px) and an intermediate feldspathic zone (I). Note diffuse margins of vein in gabbro and sharp contacts in pyroxenite.

"core". The brecciated layers contain rounded to angular gabbro blocks enclosed in a uniform gabbroic mesostasis that may be slightly more leucocratic or melanocratic than the majority of the blocks. Most of the above features may be related to the action of magmatic convection currents or mass wasting of previously crystallized cumulates. Both gabbro units are enriched in sulphides which appear to be concentrated in the upper layered gabbros.

A prominent feature of the gabbroic units is the presence of leucogabbro veins and stringers containing acicular "quench" amphiboles. These veins crosscut and parallel the layering for short distances, and locally transect both the upper and lower contacts with the pyroxenite. Where this occurs, many veins that have diffuse margins in the gabbro form sharp contacts with the pyroxenite (Plate 2-2-5). These textural and mineralogical features indicate that leucocratic vein material formed when trapped intercumulus liquids migrated out of gabbro cumulates. Migration of intercumulus liquids in this case may well have been promoted by rapid loading of the cumulate pile caused by sudden deposition of cumulates from dunite-pyroxenite density flows.

INTRUSIVE CONTACTS

Nicola–Ultramafic

Evidence of intrusion into the Nicola Group is rare. However, such relationships have been observed 0.5 kilometre south of Blakeburn Creek near the gabbro-ultramafic contact where rafts of Nicola metasedimentary rocks are intruded by gabbro and hornblendite; and in mafic pegmatite, exposed in logging scars on the western slopes of Grasshopper Mountain, which contains angular xenoliths (<40 centimetres across) of hornblende dacite derived from Nicola wallrocks.

Gabbro–Ultramafic

Relationships between gabbroic and ultramafic rocks are complex. Intrusive breccias with a net-veined texture comprising gabbro blocks set in a hornblende clinopyoxenite-hornblendite mesostasis were observed at several localities. In Newton Creek, thin (<15 centimetres) hornblende clinopyroxenite dykes intrude gabbro and both are crosscut by leucocratic gabbroic stringers (1 centimetre). In the Tulameen River, gabbroic rocks are interlayered with olivine clinopyroxenite and Findlay (1963) noted gabbro dykes cutting hornblende clinopyroxenite. These relationships point to more than one episode of gabbro crystallization as opposed to remobilization of previously solidified gabbros by the heat of ultramafic intrusion (Findlay, 1969).

Dunite–Olivine Clinopyroxenite

Thin (<20-centimetres) olivine clinopyroxenite dykes were observed to cut dunite on the southern flank of Olivine Mountain and north of the summit of Grasshopper Mountain near the dunite-pyroxenite contact. In addition, pyroxenite veins a few centimetres in width occur in clinopyroxene-bearing dunite exposed in the Tulameen River below the confluence with Britton Creek. These veins exhibit post-emplacement boudinage and may represent clinopyroxene-rich intercumulus liquids that segregated and migrated through hot dunite at the brittle-ductile transition.

Olivine Clinopyroxenite–Hornblende Clinopyroxenite

The only contact between hornblende clinopyroxenite and olivine clinopyroxenite examined in detail was that which crosses the Tulameen River near the western margin of the complex. Here, hornblende clinopyroxenite with pegmatitic masses of hornblende, clinopyroxene, biotite and magnetite grades into a medium to coarse-grained olivine clinopyroxenite cut locally by thin (<8 centimetres) dykes of finer grained pyroxenite.

Summary of Intrusive Relationships

Findlay (1963, 1969) concluded from contact relationships that the gabbroic and ultramafic parts of the complex represented two separate intrusions, an early gabbroic mass invaded by an ultramafic body in which dunite was the last unit emplaced. One outcrop in the Tulameen River section that was used to support intrusion of dunite into olivine clinopyroxenite has been re-interpreted in this study as representing the products of magmatic debris flows that incorporated partly consolidated dunite-pyroxenite layered cumulate sequences. These relationships, and the occurrence of pyroxenite dykes cutting dunite, suggest that the dunite crystallized prior to the pyroxenites. The main body of gabbroic rocks to the east appears to largely predate emplacement of the ultramafic rocks. However, thin sequences of gabbro cumulates interlayered with olivine clinopyroxenite and gabbro dykes cutting hornblende clinopyroxenite point to a protracted history of gabbro crystallization involving more than one influx of parental magma.

STRUCTURE

Structural data for the Tulameen ultramafic complex and its host rocks are presented in Figure 2-2-5.

REGIONAL FOLIATION

A penetrative foliation, generally striking north-northwest and dipping steeply to the west, is especially pronounced in Nicola metasedimentary rocks and is also evident in Eagle granodiorite and mafic-ultramafic units of the Tulameen complex (Figure 2-2-5). Within the Nicola Group, the foliation is parallel to bedding and axial planar to eastward-verging minor isoclinal folds in thinly laminated argillites, tuffaceous siltstones and crosscutting quartz veins. The axes of these folds plunge gently (5 to 20 degrees) to the north. Structures related to this phase of deformation are exposed on the Tulameen River road at the Nicola-Eagle contact. Apophyses of granodiorite that intrude Nicola marbles are boudinaged and folded about axes lying within the plane of the regional foliation (Plate 2-2-6).

CHROMITITE SCHLIEREN

The distribution and structural controls of chromitite in the Tulameen complex have important economic implications.

Plate 2-2-6. Boudinaged and tightly folded dykes of Eagle granodiorite (G) penetrating thinly bedded skarned marbles (M) and mica schists of the Nicola Group. Nicola schistosity is axial planar to folded dykes.

Extensive areas of dunite exhibit a weak to strong foliation that is variable in attitude but generally steeply inclined (Figure 2-2-3). Chromitite schlieren are commonly oriented within the foliation and serve as structural indicators for strain within the dunite. These schlieren are generally 0.5 to 2 centimetres in width and 5 to 25 centimetres in length. The most notable concentrations of chromitite were observed on the southern flanks of Grasshopper Mountain. Boudinaged chromitite layers and tight to isoclinal minor folds have been observed as well as peculiar "ring structures" that may represent cross-sections through domical folds (Plate 2-2-7). Whereas these structures are associated with the development of the foliation, other folds clearly postdate this fabric (Plate 2-2-8). In the latter case, the foliation is emphasized by micaceous alteration products (serpentine and talc) and serpentine veinlets have been folded. Evidently, the latter phase of ductile deformation took place at temperatures below the upper thermal stability limit of serpentine (<500 degrees centigrade).

Although data are sparse, there appears to be no concentric arrangement of either the foliation or chromitite schlieren within the dunite that might be expected during emplacement of a crystal mush (Findlay, 1963, 1969). However, there is some indication that radical changes in the attitude of the fabric are related to faulting, such as the change from north-

Plate 2-2-7. Chromitite layers (Cr) exhibiting ring structure (R) or condom fold in dunite, Grasshopper Mountain.

Plate 2-2-8. Hinge zone of minor fold in strongly foliated serpentinized dunite, Tulameen River road. Serpentine veinlets (Sp) lying within the foliation predate this folding event.

erly to predominantly easterly dipping structures across a north-trending fault bisecting Grasshopper Mountain. Despite these complexities, isoclinal folds in chromitite schlieren and the layer-parallel foliation within the dunite mimic structural elements in the country rocks. Thus, it seems reasonable to equate the penetrative fabric of the dunite with the regional foliation. Chromitite schlieren within the dunite presumably represent vestiges of formerly much more extensive cumulate layers.

THRUST FAULTS: TULAMEEN RIVER SECTION

Structures interpreted as thrust or reverse faults are well exposed in the Tulameen River section (Figure 2-2-3). The eastern margin of the dunite is faulted and contains a cataclastic breccia comprising rounded dunite fragments set in a serpentinized matrix. A dark grey unmetamorphosed pyritic limestone (2 metres thick) lies in fault contact with olivine clinopyroxenite. The fault plane dips 35 to 40 degrees west and is marked by a thin (1-centimetre) pale green gouge. The limestone was presumably derived from the Nicola Group and appears to have been emplaced by thrusting. We have therefore re-interpreted the contact between the dunite and olivine clinopyroxenite units mapped by Findlay (1963) as a thrust fault (Figure 2-2-3).

A major high-angle fault at the contact between the pyroxenite and the mappable gabbroic rocks is marked by a mylonite zone 3.5 metres wide containing sheared quartz veins and disseminated pyrite. The gabbroic rocks near the fault zone are heavily saussuritized, locally pyritic, cut by veins of potassium feldspar,and rarely preserve primary cumulate layering. Despite its steep attitude at the Tulameen River, the trace of this fault (Figure 2-2-3) lies subparallel to the thrust at the margin of the dunite and it too probably represents a thrust or reverse fault. An unfoliated mafic dyke intruding the mylonite zone suggests that the last fault movements were pre-Eocene.

SHEAR ZONES AND FAULTS

All of the contacts between the Tulameen complex and Nicola rocks observed in the field, with the few exceptions mentioned earlier, are ductily sheared or faulted. A package of strongly schistose to mylonitic rocks is distinguished at the northwestern margin of the Tulameen complex (Figure 2-2-3). Phyllites, chlorite-muscovite-biotite ± amphibole schists and mylonites characterized by well-developed flaser textures and amphibole augen are all represented. Contacts between the mylonitic rocks and Nicola Group are gradational and marked by increasing degrees of ductile strain, whereas the ultramafic contact appears more sharply defined by faults. In a logging scar on the western side of Grasshopper Mountain, foliated gabbros with intense mineral elongation, schistose layers and quartz rodding have been tightly folded about minor fold axes plunging up to 45 degrees west-northwest (Plate 2-2-9). These rocks were originally mapped as part of the Nicola by Findlay (1963) but they clearly include retrograde bodies of hornblende clinopyroxenite and gabbro. The margin of the intrusion in this area is interpreted to represent a ductile shear zone that has subsequently undergone folding and faulting. Another shear zone, with a similarly complex history, occurs in hornblende clinopyroxenite about 100 metres south of the summit of Lodestone Mountain.

At the eastern margin of the complex, northeast of Grasshopper Mountain, metre-wide pods of hornblendite are

Plate 2-2-9. Tightly folded mylonitized gabbros at the northwestern extremity of the complex, west of Grasshopper Mountain.

imbricated with Nicola volcanic breccias along heavily chloritized high-angle shear zones. The attitude of the contact and the planar fabric in rocks at this boundary commonly appear concordant with the regional foliation. Further south along the same shear zone, at Olivine Creek, the intensity of mineral elongation lineations in Nicola tuffs and gabbros increases dramatically toward the contact. In general, lineations due to rodding and mineral streaking developed at the margins and locally within the intrusion are gently to moderately plunging (10 to 35 degrees) to the northwest (Figure 2-2-5). Preliminary examination of kinematic indicators in the field suggests that major north-northwest-trending high-angle faults bounding the complex, and some fault zones within the complex, have a dextral component of motion.

Brittle deformation of the Tulameen complex is commonly related to northeasterly to easterly trending high-angle faults manifested by zones of intense brecciation, clay fault gouge, quartz and carbonate veining, and manganese-stained slickensided fault surfaces. Brecciated dunite is well exposed near the mouth of Britton Creek. Fragments are subangular to well rounded and cemented by coarsely crystalline serpentine (antigorite ?) and finely comminuted dunite. The breccia is tectonic in origin and localized by a northeast-trending fault along the Tulameen River (Figure 2-2-3). The northern termination of the complex is defined by a fault that has caused extensive brecciation of all exposed lithologies including Tertiary dykes. Slickensides along the fault plane indicate a vertical component of motion.

MINERAL POTENTIAL

Ultramafic and mafic rocks, and chromite-magnetite occurrences, are currently being analysed for platinum group elements (PGEs). According to St. Louis *et al.* (1986), PGEs occur in platinum-iron alloys associated with chromitite, except for palladium which is concentrated in hornblende clinopyroxenite and gabbroic rocks. The main structural control of chromitite schlieren is the penetrative foliation described above (Figure 2-2-3). However, the distribution of chromitite within the dunite "core" is not adequately known and deserves further attention in light of its economic importance. Similarly, the PGE potential of magnetite layers and schlieren on Lodestone Mountain and Tanglewood Hill remains to be more thoroughly evaluated.

Newly discovered and previously recognized sulphide localities are shown in Figure 2-2-3. The most notable new showings occur in thin gabbroic units within olivine clinopyroxenite in the Tulameen River section (Figure 2-2-4). Here, net-textured sulphides, predominantly pyrite, are disseminated throughout the rock and locally line fractures. The mineralogy and chemistry of these sulphide-rich gabbros are currently under investigation in view of the potential for remobilization of PGEs during serpentinization or precipitation of monosulphides directly from the melt (St. Louis *et al.*, 1986).

Companies currently investigating the mineral potential of the Tulameen complex include Newmont Exploration of Canada Ltd. and Tiffany Resources Inc. Newmont are systematically sampling chromitite occurrences on Grasshopper Mountain for platinum and palladium mineralization, and conducting bulk sample tests in an effort to evaluate the open-pit potential of the dunite. Tiffany Resources are re-assaying proven reserves of magnetite on Lodestone Mountain for their platinum group element potential. In addition, recently completed bulk testing of Tulameen dunite favour this rock as a suitable source of foundry olivine (G. White, personal communication, 1987).

DISCUSSION AND CONCLUSIONS

The Tulameen ultramafic complex exhibits a prolonged and complex history of penetrative ductile and brittle deformation. The oldest structures recognized in both the intrusive suite and Upper Triassic host rocks of the Nicola Group are a westward-dipping layer-parallel foliation and associated northwest-plunging minor isoclinal folds. In the opinion of the senior author, these data are consistent with an early [Late Jurassic (?) to Early Cretaceous] phase of eastward-verging isoclinal folding, although in the immediate vicinity of the Tulameen complex we have been unable to demonstrate any large-scale recumbent stratigraphy. Thrusting and imbrication of dunite and pyroxenite units of the complex are probably related to this phase of easterly directed tectonic transport. The junior author believes that the regional foliation and associated minor structures reflect a ductile shear deformation involving right-lateral slip in which the Tulameen complex behaved as a "mega-boudin". We both agree that major ductile shear zones or faults oriented along the strike of the complex were active prior to Early Tertiary (Eocene) intrusion of granitic stocks and dykes. Their inferred sense of dextral shear may be related to oblique compression associated with early thrusting, or early movements along the Fraser–Straight Creek fault system (Monger, 1985) which may have created new faults in the Tulameen region or reactivated existing reverse faults. Northeasterly and easterly trending cross faults are related to a Tertiary "transtensional" structural regime prevalent at this time in the southwestern Intermontane Belt.

Evidence for folding and thrusting of the Nicola Group by mid-Cretaceous time is found in the Cache Creek–Ashcroft area. Here, Travers (1978, 1982) documented structural elements in Nicola and Ashcroft strata that are remarkably similar to those described above in the Tulameen region. Furthermore, he demonstrated the presence of large-scale recumbent folding and easterly directed thrusting in response to eastward overthrusting of Cache Creek terrane on Quesnellia (*see* Figure 2-2-1). Using these data, Monger (1985) speculatively linked the eastern boundary of the southern Mount Lytton plutonic complex (Eagle plutonic complex) with its southwestern dipping gneissosity and adjacent concordant schist belt (Nicola Group) with the eastward-verging structures near Ashcroft. The senior author's interpretation of the structure of the Tulameen complex and Nicola host rocks lends support to his speculation that the two regions represent different structural levels of the same fold and thrust package.

Findlay (1963, 1969) interpreted ultramafic rocks of the Tulameen complex as reflecting an original igneous zonation formed in a "proto-stratiform" laccolith-like body in the order dunite, olivine clinopyroxenite, hornblende clinopyroxenite. The zonal configuration of units expressed in outcrop was formed subsequently during forcible emplacement of the dunite layer (or "core"), intruded as a partly consolidated crystal mush into overlying pyroxenites (or "shell"). The dunite provided a "piston-like" locus of stress for deformation and tilting of overlying gabbroic and surrounding country rocks. Crystallization and emplacement were regarded as partly synchronous with regional deformation of Upper Triassic Nicola rocks in order to explain the lack of well-developed cumulate layering within the complex.

In this study, it has been argued that the transgressive character of the main dunite body in relation to its pyroxenite "shell" is a consequence of thrusting during the development of Late Jurassic (?) to Early or mid-Cretaceous eastward-verging regional structures. At least one other thrust or reverse fault separates olivine clinopyroxenites from gabbros in the Tulameen River section and imbrication by thrusting or infolding may partly explain the intricate repetition of pyroxenite and gabbro units in the eastern and southern parts of the complex. The elongate outcrop pattern of the intrusion reflects not only this deformation but high-angle strike-slip faulting with an inferred sense of right-lateral displacement of unknown magnitude.

The structural evolution of the Tulameen complex inferred above precludes any firm assessment of original intrusion geometry. However, gradational contacts among pyroxenite units (especially in the western half of the complex), interlayered dunite-pyroxenite cumulates, and evidence for a common petrogenetic affiliation (Findlay, 1969) support Findlay's concept of a single differentiated intrusive body. Given a sill-like geometry, deeper stratigraphic levels appear to be exposed by thrusting in the northern part of the complex.

Emplacement of ultramafic units as a crystal mush is unlikely to preserve delicate sedimentary structures such as those observed in thin gabbroic units within olivine clinopyroxenite. The general lack of magmatic layering is at least partly attributable to periodic remobilization and slumping of cumulate sequences penecontemporaneous with deposition; and tectonic reworking of cumulate stratigraphy (for example, disruption of chromitite layers in dunite by flowage during regional deformation). The contemporaneity of intrusion and regional tectonism will no doubt be elucidated by detailed petrofabric studies and further age dating now in progress. However, there is nothing in the existing data that precludes deformation and thrust emplacement of the Tulameen ultramafic complex in an essentially cold, completely solidified state.

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