THE ANATOMY OF THE SHULAPS OPHIOLITE

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INTRODUCTION

The Shulaps ultramafic/mafic complex is exposed in the mountains of the Shulaps Range, within the Tyaughton Creek map area (Schiarizza *et al.*, 1989) approximately 50 kilometres northwest of Lillooet in the Cordillera of southwestern British Columbia (Figure 3-4-1). It forms one of the largest bodies of ultramafic rocks in the orogenic belt, underlying an area of approximately 180 square kilometres. The complex is situated along the boundary of the Intermontane and Insular superterranes (Monger *et al.*, 1982), which is marked in the area by the Yalakom fault system. Its origin and structural evolution have important bearing on unravelling the tectonic collage of suspect terranes that form this part of the Cordillera (Price *et al.*, 1985; Potter, 1986; Rusmore, 1987).

The Shulaps complex was first mapped in detail by Leech (1953), who concluded that the peridotites were part of a nonstratiform plutonic complex that was later intruded by smaller lenses of gabbro and pyroxenite. More recently, Nagel (1979) and Wright *et al.* (1982) have suggested an ophiolitic origin for the peridotite complex, interpreting it as a residual mantle tectonite section. These workers established that the western basal contact of the complex is a serpentinite mélange containing exotic blocks of sedimentary and volcanic rocks. These rocks are tentatively correlated with supracrustal rocks in the oceanic Bridge River Terrane, which structurally underlies the mélange. The mélange also contains blocks of ultramafic and mafic plutonic rocks which may represent fragments of Layer 3 of the Bridge River oceanic crust. Leech (1953), Nagel (1979) and Wright *et al.* (1982) have suggested that stratigraphic relationships exist

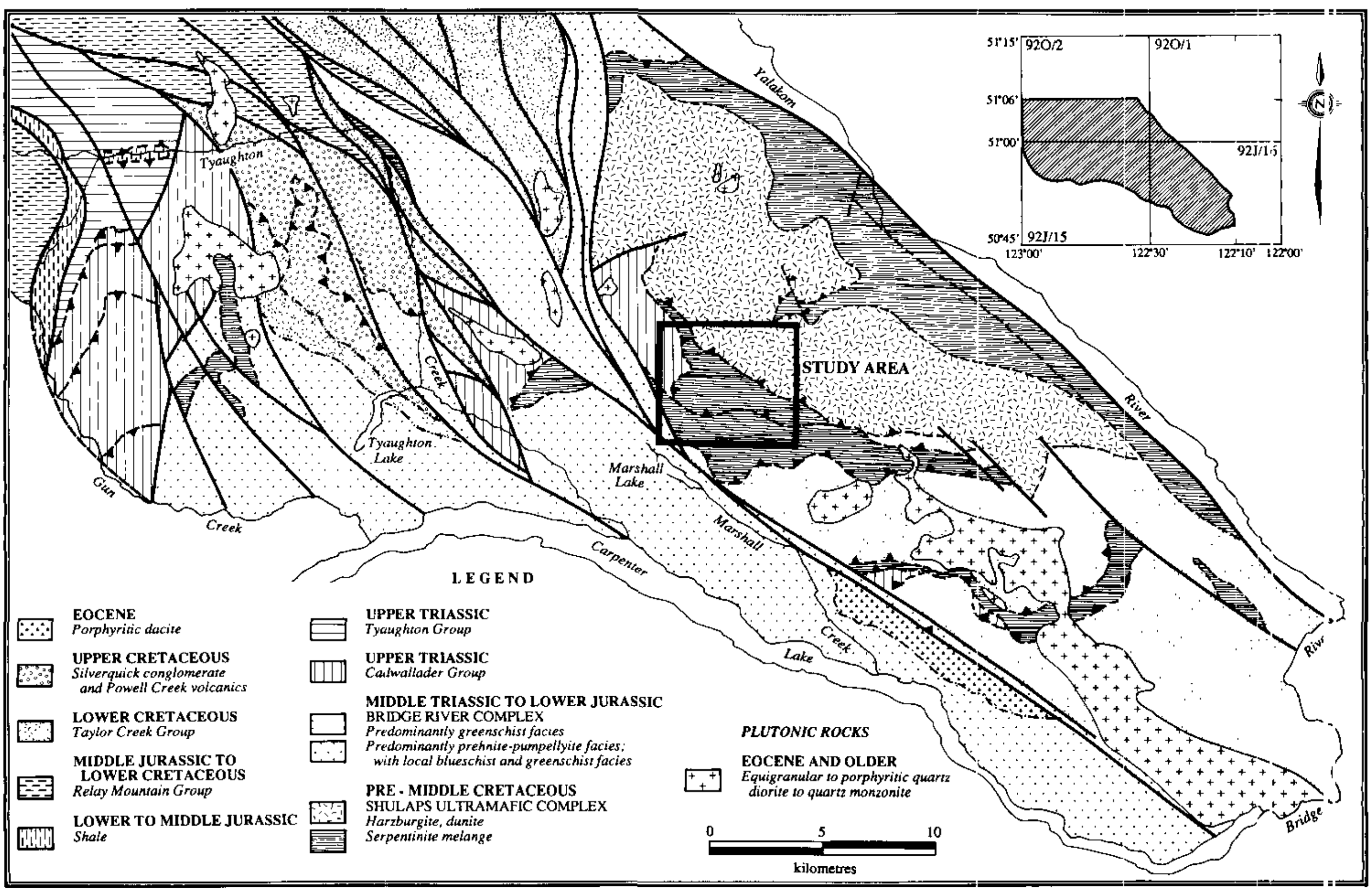


Figure 3-4-1. Regional setting of Shulaps ophiolite complex and location of the study area.

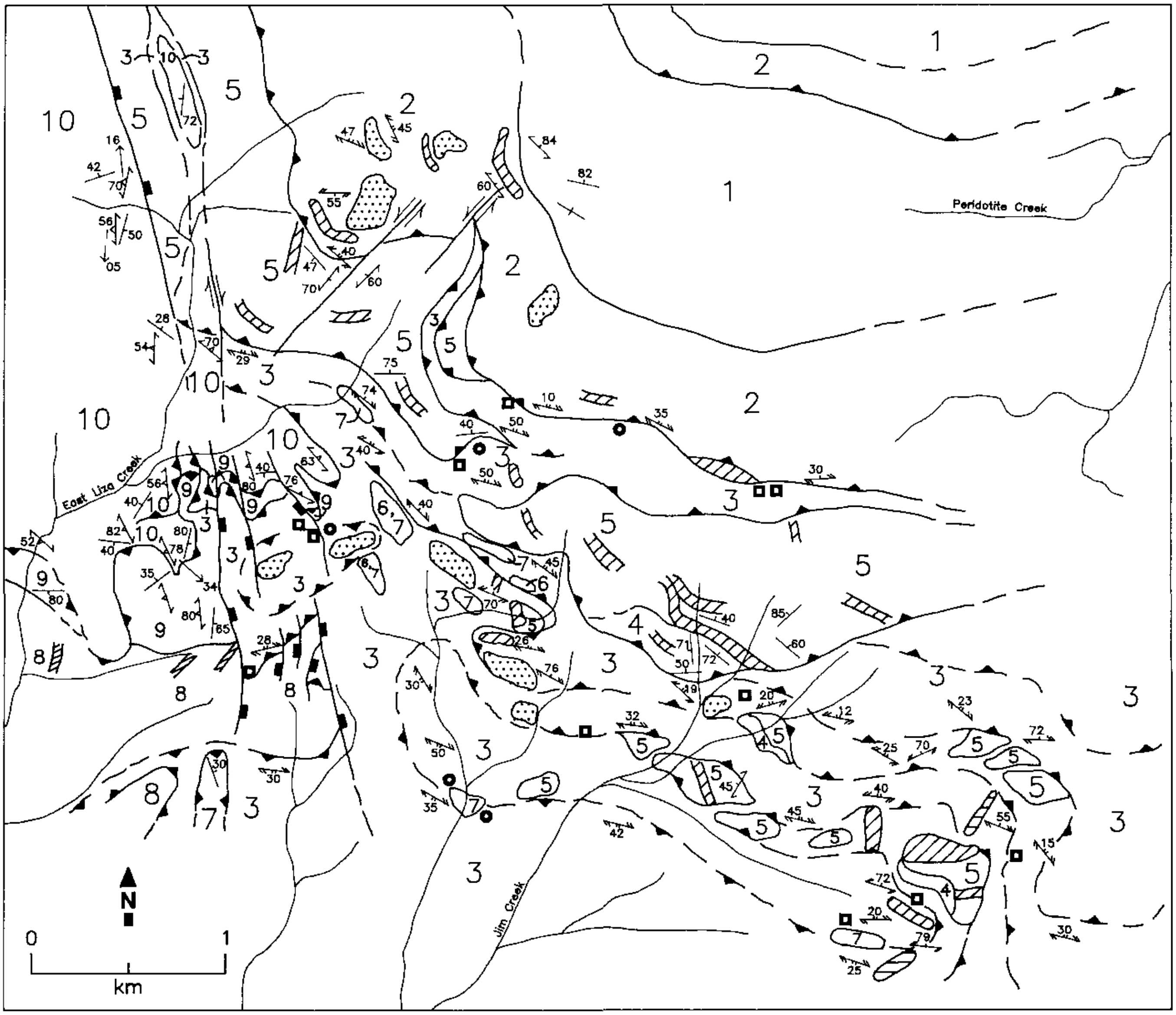
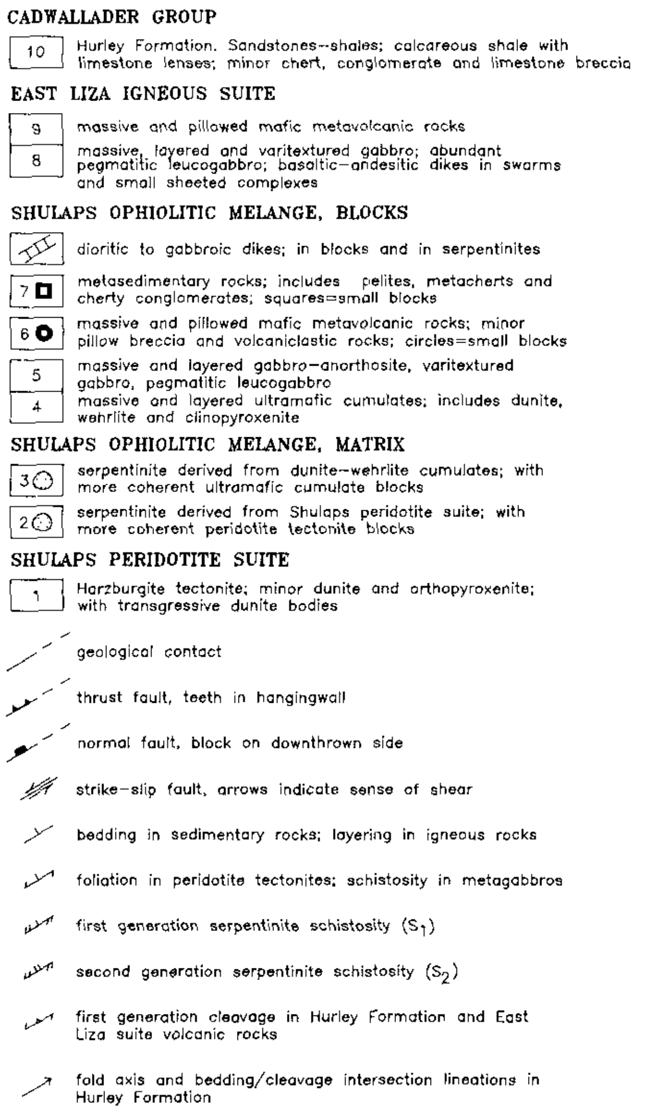


Figure 3-4-2. Schematic geological map of the study area, with legend.

between gabbroic and volcanic rocks within blocks in the mélange, implying that the basal mélange of the Shulaps complex may represent the highly dismembered remnants of a more or less complete ophiolitic suite. A segment of a Triassic sedimentary apron (Hurley Formation) of the Cadwallader volcanic arc assemblage (Rusmore, 1987) lies with fault contact directly to the west of the Shulaps complex. According to Rusmore (1987) and Potter (1986), the more or less contemporaneous Cadwallader arc and Bridge River ocean basin became juxtaposed during movement on the Shulaps sole thrust. Since this thrust has an overall westerly vergence (Potter, 1986), the arc restores palinspastically to the west of the basin. The Bridge River ophiolitic assemblage may thus have developed in relation to back-arc spreading (Potter, 1986).

To date, no modern account exists of the petrogenesis and structural evolution of the mantle peridotite section of the Shulaps complex and the underlying ophiolitic mélange. Further, the stratigraphic and structural relationships of the Bridge River Terrane, the adjacent fault-bounded Cadwallader Terrane and the Shulaps complex remain obscure. This study was undertaken primarily to establish the tectonic and plutonic evolution and petrogenesis of the Shulaps ophiolite complex and its Mesozoic accretionary history. Detailed geological mapping on scales ranging from 1:6000 to 1:14 000 was carried out in a two-week period in summer 1988 and a four-week period in the summer of 1989, covering an area of approximately 20 square kilometres centred around the upper courses of Jim Creek and East Liza Creek, along the southwestern edge of the Shulaps complex (Figure 3-4-2). This area comprises the critical transition from coherent thrusts sheets of residual mantle peridotite of the Shulaps complex to underlying ophiolitic mélange. It contains the bulk of the exotic blocks of gabbro and pyroxenite in the mélange, together with less abundant smaller blocks of volcanic and sedimentary rocks. In addition, on the western



side it covers a small segment of the contact with sedimentary rocks of the Hurley Formation in the Cadwallader Group. This report provides a detailed description of the lithological units and their structural relationships in this study area.

LITHOTECTONIC SUBDIVISION

The map units in the study area may be conveniently subdivided into four main lithotectonic units (Figure 3-4-2), which are in thrust contact with one another and display the following stacking order, from structural top to bottom:

(1) The Shulaps peridotite suite, exposed in the northern part of the study area (Unit 1).

(2) The Shulaps ophiolitic mélange, which is exposed along the southwestern margin of the peridotite suite and occupies the central and southern part of the map area (Units 2 to 7);

(3) The East Liza igneous suite of mafic plutonic and volcanic rocks, exposed in the southwestern part of the study area (Units 8 and 9);

(4) The Cadwallader Group, which comprises sedimentary rocks of the Hurley Formation and is exposed on the west flank of the Shulaps complex and East Liza suite (Unit 10).

Together, these four units comprise a complicated, polyphase, southwesterly verging, linked thrust system, which at a later stage became overprinted on its western flank by a transtensional high-angle fault system.

The Shulaps peridotite suite occupies the upper part of the thrust system. It extends far to the north and east of the study area (Figure 3-4-1) and underlies the highest peaks within the Shulaps Range. Work by Leech (1953) and Wright *et al.* (1982) suggests that it consists entirely of variably serpentinized, layered harzburgite tectonites with locally abundant dunite bodies. Preliminary field observations suggest that the upper thrust unit of mantle peridotite consists of a shingled array of moderately northeast-dipping thrust sheets of more or less coherent peridotite, separated from one another by shear zones consisting of intensely foliated serpentinite. The unit has been interpreted by Wright *et al.* (1982) as an obducted fragment of depleted oceanic upper mantle.

The Shulaps ophiolitic mélange occurs in a northwest trending belt, up to 5 kilometres wide, along the southwestern edge of the Shulaps peridotite suite. It is spectacularly exposed along the southwestern slopes of the Shulaps Range. To the northwest, it terminates abruptly against a high-angle fault system which marks the boundary between the Shulaps complex and a fragment of the Cadwallader Terrane. To the southeast, the belt extends into the Hog Creek imbricate zone delineated by Potter (1983). The mélange underlies the imbricate thrust system of the Shulaps peridotite suite with a moderately northeast-dipping structural contact. Potter (1983, 1986) has shown that the belt overlies, with gently east-dipping thrust contact, metasedimentary and metavolcanic units of the Bridge River complex directly southeast of the study area. The belt thus constitutes a partly exhumed duplex structure that defines the boundary zone between an upper plate consisting of a telescoped section of oceanic upper mantle peridotite and a lower plate of telescoped oceanic supracrustal sequences.

Internally, the mélange belt comprises a number of smaller duplexes which form an extension of the Hog Creek imbricate zone. These duplexes may be subdivided in terms of both the protolith types of the serpentinites that make up the voluminous matrix of the mélange belt, and the igneous and sedimentary lithologies that occur as abundant blocks within the serpentinite matrix. The matrix of the mélange is subdivided in two northwest-trending belts which maintain a consistent structural position in the thrust system. The serpentinite matrix of the upper belt is derived from low-temperature alteration of protoliths found only in the overlying mantle peridotite suite, whereas the protoliths of the lower belt comprise a suite of ultramafic cumulate rocks including dunite, wehrlite and clinopyroxenite. Within each belt these protoliths are locally preserved in more or less coherent blocks enveloped by intensely sheared serpentinite. The ultramafic cumulate protoliths also occur at the bases of two gabbroic blocks within the ultramafic cumulate-derived serpentinite belt.

Both mélange belts contain abundant boudins and more coherent sections of gabbroic to dioritic dikes which locally preserve chilled margins and contact aureoles of porphyroblastic olivine-talc-serpentine schists (Leech, 1953; Nagel, 1979). However, a clear distinction can be made between the two belts as regards the occurrences of blocks representing dismembered ultramafic-mafic plutonic complexes, as well as blocks of sedimentary and volcanic rocks. The mantle-peridotite-derived serpentinite mélange does not appear to contain any such blocks in the area studied. The most extensive belt of plutonic blocks is situated directly beneath the basal mantle-peridotite-derived serpentinite shear zone and preserves the thickest coherent section of ultramafic cumulates observed in the area. Moreover, blocks of plutonic complexes situated structurally lower in the ultramafic-cumulate-derived serpentinite mélange comprise generally only higher level gabbroic sections of the plutonic complexes. Sedimentary and volcanic blocks are irregularly distributed throughout the lower serpentinite belt, but are particularly prominent in number and size directly beneath the main belt of plutonic blocks.

The East Liza igneous suite forms a separate thrust unit of limited extent in the southwestern part of the map area. It is structurally overlain by the ultramafic-cumulate-derived serpentinite mélange, and overlies intensely folded units of the Hurley Formation with marked thrust contact. In the south it comprises gabbros which in all field aspects resemble those of the main gabbro blocks within the mélange. To the north, the gabbros appear to be in nonconformable stratigraphic contact with overlying volcanic rocks in a poorly exposed area dominated by abundant outcrops of dikes with screens of volcanics. The unit is equivalent to the greenstone-gabbro complex of Leech (1953).

Sedimentary rocks of the Late Triassic Hurley Formation of the Cadwallader Group occupy the western part of the map area. They comprise an upward-fining sequence of siliciclastic turbidites including some volcaniclastic rocks, associated limestone breccia and bedded chert. In the northwest, the unit is in abrupt, high-angle fault contact with a block of gabbro within the serpentinite mélange. Farther south, it occurs in a number of half windows beneath the mélange and the volcanic rocks of the East Liza suite. Rocks resembling Hurley lithologies also occur as exotic blocks within the serpentinite mélange.

LITHOLOGY AND STRUCTURE OF MAP UNITS

SHULAPS PERIDOTITE SUITE (UNIT 1)

The Shulaps peridotite suite comprises the bulk of the ultramafic rocks in the Shulaps complex as defined by previous workers (e.g., Leech, 1953; Wright *et al.*, 1982), and is exposed in the northern part of the study area. The rocks form part of a coherent basal thrust sheet of mantle peridotite that strikes northwest, dips 40° to the northeast, and is approximately 300 metres thick. The sheet is bounded at its top and bottom by serpentinite shear zones up to 500 metres thick. The boundaries are sharp structural contacts which are parallel to schistosity in the serpentinite matrix of the shear zones.

Lithologies within the peridotite sheet are dominantly layered and massive, foliated harzburgite with subordinate dunite and orthopyroxenite. Compositional layering is defined on centimetre to metre scale by modal variations in the orthopyroxene content of the harzburgite, and by parallel phase boundaries between harzburgite, dunite and orthopyroxenite. Numerous irregularly shaped pods of dunite occur within the peridotite. They are variable in size, ranging from less than a metre to several tens of metres in diameter. The dunites cut across the peridotite tectonite fabric in an irregular manner and the margins of the bodies appear undeformed. Most bodies contain abundant disseminated chromite and thin chromite stringers with variable orientations. The chromite grains range up to 1 centimetre in size and are generally euhedral.

A penetrative mineral foliation and lineation, which in most localities is parallel to the compositional layering, is observed in the harzburgite. Foliation and lineation are defined by a weak to moderate preferred orientation of orthopyroxene and spinel grains varying in size from 1 to 15 millimetres. The linear aspect of the fabric is outlined by chromite pull-apart textures. The texture of the peridotite tectonites can be classified as protogranular to mildly porphyroclastic. Mesoscopic folds of layering with associated axial planar foliation have not been observed. Layering and parallel foliation have rather constant orientation, dipping steeply to the north-northeast or south-southwest. Mineral elongation lineations are subvertical in the foliation plane. According to data from Leech (1953) and Wright *et al.* (1982), the regional attitude of layering and foliation in the Shulaps complex as a whole is similar to that observed in the study area, with steep southwesterly dips predominating. The attitude of the planar fabrics is markedly oblique to the fabric of the serpentinite shear zones in which the main serpentine foliation has a moderate northeasterly dip.

MANTLE-PERIDOTITE-DERIVED SERPENTINITE MÉLANGE (UNIT 2)

The unit forms a zone 300 to 500 metres thick that dips, on average, at an angle of 40° to the north and northeast, beneath the basal thrust sheet of the mantle peridotite suite. It structurally overlies the belt of large gabbro blocks which form the steep cliffs in the western part of the map area. Farther to the east, the unit directly overlies the ultramafic-cumulate-derived serpentinite belt (Unit 3) on the upper the upper slope of Shulaps Peak. Where the intervening main gabbro-block level is missing, the contact between the two serpentinite belts may be difficult to identify. However, suitable outcrops of matrix rocks which show transitional stages of alteration of the different protoliths are readily available on both sides of the contact in most areas.

The main structural grain of the belt is defined by a braided network of narrow zones containing an intensely schistose scaly serpentine fabric showing abundant evidence, in the form of fibrous serpentine slickensides, for reverse dip slip and oblique slip. Locally these serpentinite strands have a mylonitic aspect containing well-developed C-S fabrics which invariably indicate southwest-directed thrusting. This fabric is referred to as the second generation serpentine schistosity (S_2) in the legend of the geological map. It constitutes the younger component of a composite serpentinite fabric that can be observed in lozenge-shaped serpentinite blocks surrounded by the S_2 serpentine zones. Within such blocks an older schistosity (S_1) is generally inclined at a high angle to the main serpentinite shear zone fabric and bends gradually or abruptly into the late fabric at the edges of the blocks. Locally the first generation serpentine schistosity has itself the appearance of a fine scale C-S fabric.

ULTRAMAFIC-CUMULATE-DERIVED SERPENTINITE MÉLANGE (UNIT 3)

This component of the mélange occupies most of the eastern and southern parts of the map area. It extends eastwards into the Hog Creek imbricate zone delineated by Potter (1983). Previous workers have tacitly assumed that the serpentinite matrix of the mélange, as a whole, was derived from the overlying mantle peridotite suite. The present study, however, has revealed that this is only true for the upper part of the mélange (Unit 2). The matrix of the lower part consists entirely of serpentinite derived from ultramafic cumulates. The main lithologies that acted as protoliths are wehrlite and dunite, with lesser clinopyroxenite. The protolith types of the serpentinite matrix are identical, in all aspects, to ultramafic cumulates found as coherent sequences at the bases of two large blocks comprising segments of an ultramafic to gabbroic plutonic complex (Units 4 and 5, see following section for description).

The macroscopic structure of the ultramafic-cumulate-derived serpentinite mélange is that of a huge duplex, sandwiched between the overlying thrust system of the mantle peridotite suite and the underlying thrust system of variably deformed and metamorphosed supracrustal rocks of the Bridge River complex in the east (Potter, 1983, 1986), and the thrust stack of the East Liza suite and Hurley Formation in the west. The belt reaches a structural thickness of approximately 1 kilometre in the eastern part of the area. A number of smaller, flat-roofed, hinterland-dipping duplex structures have been mapped within the belt (Figure 3-4-2). These duplexes are focused on shingled stacks of large and smaller blocks of the ultramafic-gabbroic plutonic complex which are situated on at least three different structural levels within the belt. The roof and floor thrust zones of the duplexes are outlined by gently to moderately north to northeast-dipping zones of intensely schistose scaly serpentinite (S_2), similar in style and orientation patterns to the second generation serpentinite shear zones observed in the overlying mantle-peridotite-derived mélange belt. Within the duplexes, the first generation serpentine schistosity generally dips more steeply to the north or northeast and curves into the duplex boundaries. This schistosity often wraps around the lozenge-shaped plutonic blocks contained in the duplexes, creating the appearance that originally much larger coherent sections of the plutonic complex were telescoped along shear zones injected by serpentinite. The S_2 serpentinite strands commonly display C-S mylonite fabrics, particularly in contact zones with larger blocks in the mélange. Shear-sense indicators invariably provide evidence for southwesterly thrusting. The volcanic and sedimentary blocks are all contained within S_2 serpentinite strands and are consistently aligned with their longest dimensions parallel to the S_2 fabric.

The overall attitude of the duplex structures is remarkably flatlying in the southwestern and southeastern parts of the belt but steepens to northerly and northeasterly dips of 40° to 50° at the contact with the overlying mantle peridotite thrust system (Figure 3-4-2). Most of this change in attitude seems focused on the main belt of plutonic blocks situated along this contact, and it appears as if these big blocks acted as a footwall ramp to the overlying thrust system. A similar ramp structure, outlined by flat and steep S_2 belts in the floor thrust zone of the mélange, is created by the underlying thrust stack of East Liza suite and Hurley Formation, exposed in the half window in the western part of the area (Figure 3-4-2). In the south, the main S_2 fabric dips gently to moderately to the south, creating a broad antiformal zone along the upper reaches of Jim Creek. This structure may mark the location of a blind culmination in the footwall of the mélange, which is possibly an easterly extension of the East Liza suite–Hurley Formation thrust stack.

BLOCKS OF ULTRAMAFIC-MAFIC PLUTONIC COMPLEXES

A number of large and small coherent blocks in the lower serpentinite belt represent dismembered sections of a plutonic complex (Plate 3-4-1). They include a large variety of intrusive rocks ranging from olivine-rich ultramafic cumulates to high-level, varitextured plagioclase-rich gabbros. They display complex multiple intrusive relationships often involving a number of igneous phases, and they exhibit, at

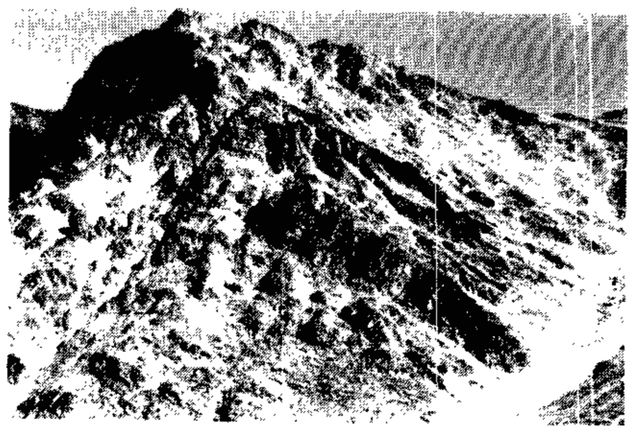


Plate 3-4-1. View to the northwest of the eastern edge of the main gabbro block in the mélange. Lower half of section in block comprises recessively weathering screens of massive and layered ultramafic cumulates between more resistant dikes. Upper half of section comprises screens of a variety of gabbro types between dikes. The contact between ultramafic and gabbroic rocks lies along the thick dike seen in centre of the photograph. The gabbroic to dioritic dike swarm dips moderately to steeply northeast and shows complex internal geometry (resistant dikes in centre of photograph).

least locally, evidence for heterogeneous high-temperature plastic deformation associated with intrusive events.

ULTRAMAFIC CUMULATES (UNIT 4)

The ultramafic cumulates are mainly found in two blocks, where they form the present structural base of the plutonic sequences (Figure 3-4-2). Their most important occurrence is in the large block in the centre of the belt. This sequence reaches a total thickness of at least 200 metres and extends along strike for at least 500 metres. It comprises dominantly wehrlite and clinopyroxenite, with subordinate chromitiferous dunite, clinopyroxene-bearing dunite, olivine clinopyroxenite and rare olivine websterite. Plagioclase may be present, in a highly altered state, in some of the pyroxenites. The suite was previously described as the clinopyroxenite unit by Leech (1953) and Nagel (1979). Both authors clearly underestimated the total average modal amount of olivine in the suite in favour of clinopyroxene.

The present base of the suite is poorly exposed, but appears to be in structural contact with underlying serpentinite with a moderately northeast-dipping S_2 fabric. In the eastern outcrop area of the block, the top of the unit is defined by a 20-metre-thick, little-deformed diorite dike with well-developed chilled margins. This dike is immediately overlain by thinly layered gabbros. Internally, the ultramafic suite contains a number of small, fault-bounded enclaves of layered gabbro. It is also cut by a narrowly spaced diabase dike swarm that dips on average 55° north-northeast. The ultramafic cumulates thus occur as narrow screens between the late dikes (Plate 3-4-1).

The plutonic geometry of the ultramafic suite in the main block is highly variable. The rocks are generally poorly layered to massive, and have isotropic texture with anhedral olivine shapes and randomly orientated stubby diopside prisms predominating. Where phase layering is observed, it is usually nonplanar and highly discontinuous over short distances. Layering attitudes are extremely variable from screen to screen in the dike swarm. It is not clear whether this is an original plutonic feature, or an imposed feature due to rotation caused by dike intrusion. The suite comprises poorly defined cyclic sequences of phase-graded units with a basal clinopyroxene-bearing dunite layer, grading into a thick wehrlite layer followed by a thick olivine clinopyroxenite layer. Olivine-rich phases often occur as irregular, pod-like bodies within clinopyroxene-rich phases. Poikilitic textures of clinopyroxene with olivine and chromite inclusions occur occasionally in wehrlitic phases. In most rocks clinopyroxene appears to be the main adcumulus phase.

GABBROIC SEQUENCES (UNIT 5)

The gabbroic sequences constitute the most voluminous component of the plutonic blocks in the mélange, as was already noted by Leech (1953) and Nagel (1979). In all blocks complex intrusive relationships between various gabbroic phases are indicated by crosscutting phase domains, xenolith-charged margins of late intrusive stocks, structurally controlled phase boundaries including faults and shear zones, fault-bounded ultramafic cumulate enclaves in gabbroic sequences, and late intrusive dike swarms (Plate 3-4-2). The scale of these features is generally small, on average 10 to 50 metres of outcrop width. They suggest that the gabbro complexes did not evolve through crystallization in large magma chambers of simple geometrical form, but rather through spatially and temporally highly variable multiple intrusive processes.

Compositionally, the gabbroic suite ranges from clinopyroxenite and rare websterite to two-pyroxene gabbros, clinopyroxene-rich gabbros and anorthosite. Clinopyroxene and plagioclase are the dominant constituents, whereas olivine and orthopyroxene are relatively rare. Undeformed gabbros range texturally from massive to layered, and isotropic to foliated. Medium to coarse-grained pegmatitic varieties, especially leucogabbros, are common in the form of small stocks and irregularly shaped pods and veins. High-level, varitextured gabbros are the dominant component in most of the blocks in the mélange belt. They constitute the top sections of the large plutonic blocks and form the only constituent of the remaining blocks. Fine scale compositional layering, occasionally with grain-size graded or phase-graded aspect (Plate 3-4-3), is common in a number

Plate 3-4-2. Typical appearance of high-level, varitextured gabbro. It comprises sheared and isotropic gabbro, crosscutting pegmatitic leucogabbro veins and, behind the hammer, a late isotropic diabase dike.

of localities. The layering displays highly variable attitudes, even within small areas of a single block. Domains of constant layer attitude are invariably bounded by crosscutting varitextured suites, by discrete dikes of variable width, or by shear zones and faults.

Domains of penetrative plastic deformation are rare in most of the blocks. Locally, layered and massive gabbros contain a well-developed schistosity (subparallel to layering, where present) and mineral elongation lineation. These rocks have a porphyroclastic texture of coarse clinopyroxene with recrystallized rims of green hornblende, suggesting that deformation occurred under amphibolite facies conditions. The deformed gabbros are commonly cut by pegmatitic leucogabbro bodies and a variety of gabbroic to dioritic dikes. Narrow, low-temperature shear zones, characterized by chlorite alteration, are common throughout the gabbro blocks and they are generally located along macroscopic phase contacts. The shear zones are truncated by younger intrusive rocks, indicating that they developed during the magmatic evolution of the gabbroic complexes.

Plate 3-4-3. Fine-scale, phase-graded layering in gabbro-anorthosite sequence which forms an isolated plutonic unit within the eastern part of the main gabbro block. This gabbro sequence is in fault-controlled, intrusive contact with a large xenolith of ultramafic cumulates shown on the right-hand side of the photograph. The resistant dark-weathering unit above the layered gabbro is a crosscutting diorite dike with chilled margins against gabbro.

BLOCKS OF SEDIMENTARY AND VOLCANIC ROCKS (UNIT 6 AND 7)

The ultramafic-cumulate-derived serpentinite belt contains a number of blocks (approximately 30) of sedimentary, volcanic and volcaniclastic rocks in the study area. Such blocks have also been reported by Potter (1983) from the Hog Creek imbricate zone. Whereas the plutonic blocks in the serpentinite can reasonably be considered as indigenous to the belt, the blocks of supracrustal rocks represent a truly exotic element, justifying the use of the term mélange.

Most blocks are rather small in size, their longest outcrop dimension rarely exceeding 200 metres. Larger blocks tend to be tabular in shape with tapered edges. They are generally aligned parallel to the S_2 fabric in the surrounding serpentinites, with their longest dimension trending parallel to the regional strike of the belt Smaller blocks, up to 10 metres in size, have a more rounded shape, and may lie inclined to the S_2 serpentinite fabric. The largest concentration of blocks is in a mylonitic serpentinite zone situated directly beneath the large plutonic blocks near the top of the belt, in the central and western part of the map area. Another conspicuous string of larger blocks lies lower in the belt in the easternmost part of the area, and appears to extend into the Hog Creek imbricate zone to the east.

The sedimentary blocks (Unit 7) comprise mainly bedded and massive chert, and thin to medium-bedded turbiditic siltstone and sandstone. In one block, bedded chert is interlayered with a unit of strongly silicified and mineralized volcanic rocks 10 metres thick. Small blocks of recrystallized limestone, limestone breccia, and cherty matrix-supported pebble conglomerate with abundant felsic igneous clasts are rare. One small block of coarse pyroclastic rock was found in Jim Creek near a block containing an upward-facing 20-metre sequence of pyritiferous laminated shale-siltstone, white bedded chert with shale partings, and massive greywacke with siltstone rip-up clasts. This sequence appears correlative with a more extensive unit of siliciclastic rocks with interbedded chert and rare volcaniclastic rocks which is exposed on the lower slopes west of

Plate 3-4-4. Detail of highly schistose, thinly layered quartz phyllite, cut by brecciated quartz diorite dike in sedimentary knocker within the serpentinite mélange in the easternmost part of the study area.

Jim Creek (Schiarizza *et al.*, 1989). The large block in the southeastern part of the map area contains an intensely foliated sequence of thinly layered pelites cut by small brecciated pods and dikes of hornblende plagioclase porphyry (Plate 3-4-4) that do not extend into the adjacent serpentinite matrix (*see* also Archibald *et al.*, 1989). Most blocks show effects of lower greenschist facies metamorphism associated with deformation in the form of cleavage development and, locally, mesoscopic cleavage folding.

Volcanic blocks (Unit 6) are less abundant than sedimentary blocks. They comprise massive and pillowed lava and pillow breccia. In some localities, the lavas show variolitic and/or vesicular texture; some contain feldspar phenocrysts and chlorite pseudomorphs presumably after primary pyroxene or amphibole. Pillow breccias locally contain lenses of chert and limestone breccia up to several metres in size. The volcanic rocks appear to range from basaltic to dacitic in composition. They are generally strongly altered due to silicification and low greenschist facies metamorphism, and show heterogeneous deformation in the form of flattening of pillows and cleavage development in the matrix of pillow breccias.

Dikes in Serpentinite Mélange

Numerous disrupted fragments of dikes occur within both types of serpentinite belts. They range in composition from gabbroic to dioritic; hornblende-porphyritic quartz diorite is an abundant component of the dike suite. Some large dikes in the eastern part of the area are multiple intrusive, ranging in composition from pyroxenite to gabbro and flow-banded, feldspar-porphyritic diorite (Plate 3-4-5). Many gabbroic dikes are strongly altered to either rodingite, greenschist or talc schist. On the other hand, many dioritic dikes are remarkably fresh and preserve well-developed chilled margins.

The dike fragments display a variety of shapes reflecting the degree of their deformation and related alteration. They range from small to large, rounded or lozenge-shaped boudins to rather straight and continuous dike segments, some of which extend up to 100 metres along strike. Boudins are completely surrounded by foliated serpentinite and are aligned parallel to either S_1 or S_2 as the main external fabric. They often occur in clusters with conspicuous parallel or en echelon alignment in the serpentinite fabric, reflecting boudinaged single dikes originally oriented parallel or oblique to the external fabric, respectively. Some clusters, however, are so dense that they must have resulted from boudinage of parallel dike swarms. Straight dike fragments of the dioritic suite generally preserve chilled margins against either the S_1 or S_2 fabric of the serpentinite matrix. Their contacts are, however, invariably sheared, and the fine-grained chill zones often show foliation development related to postintrusion deformation of the serpentinite matrix. The field relationships indicate that both pre-S_1 and post-S_2 dike suites are present in the mélange (*see* below). Gabbroic dikes define both early and late dike suites, whereas dioritic dikes (particularly those with preserved chilled margins) are almost all post-S_1. Dikes in the mantle-peridotite-derived serpentinite belt are relatively rare compared to the abundant occurrences in the ultramafic-cumulate-derived serpentinite belt. They are dominantly part of the late dioritic suite intruded along S_2 shear zones near the upper and lower contacts of the belt.

Plate 3-4-5. Detail of composite dike fragment in eastern part of the serpentinite mélange. Flow-banded quartz diorite dike, with feldspar phenocryst alignment, is intrusive into sheared and altered isotropic gabbro.

Late dikes have locally imprinted contact metamorphic effects on the surrounding serpentinite. The most common contact metamorphic assemblages are olivine + serpentine ± talc, and olivine + talc ± magnesite. The rocks have a porphyroblastic texture of elongate olivine crystals in a white felted matrix. The porphyroblasts are often pseudomorphed by fine-grained, brown-weathering magnesite + talc aggregates. These rocks were first recognized by Leech (1953) and later studied in some detail by Nagel (1979), who correctly suggested that the olivine schists formed by prograde metamorphism of originally low-temperature serpentinite. He concluded that the olivine was generated at temperatures around 400°C, but ignored the effects of Xco_2. This is probably erroneous in view of the common occurrence of magnesite in the assemblage; high Xco_2 would slightly lower the temperature range for the stability of olivine in the contact aureoles. Nagel inferred a magmatic source for the heat that caused the static metamorphism, but did not link the heat source directly to the abundant dike suites in the mélange. The present study has shown that some contact aureoles are still attached to the dike walls, whereas others have been detached from the dikes by later shearing that led to the development of the S_2 serpentine schistosity. The latest widespread dike intrusion event recorded in the mélange is thus interpreted to be syn-S_2.

EAST LIZA IGNEOUS SUITE (UNITS 8 AND 9)

The suite is treated as a separate lithotectonic unit, in contrast to the interpretation of Nagel (1979) who considered it to be a block in the serpentinite. It is overlain with clear thrust contact by ultramafic-cumulate-derived serpentinites along its eastern and southern margins (Plate 3-4-6). It structurally overlies sedimentary rocks of the Cadwallader Group, and nowhere in the study area can it be shown to be underlain by serpentinite. The floor thrust of the serpentinite mélange is thus drawn at the top of the unit and defines a broad easterly plunging antiform that extends eastward into the Hog Creek imbricate zone.

The unit comprises mafic to intermediate intrusive and extrusive rocks displaying complicated igneous relationships. Leech (1953) and Nagel (1979) have suggested that a transitional contact exists between gabbros and volcanic rocks. Gabbroic rocks underlie the southern part of the outcrop area and appear to be overlain with nonconformable stratigraphic contact by pillowed lavas in the north. The contact zone is poorly exposed, but local field relationships suggest that it dips gently north-northeast.

The intrusive sequence (Unit 8) consists mainly of fine-scale layered two-pyroxene gabbros with minor interlayered websterite, clinopyroxenite and anorthosite (Plate 3-4-6). These rocks show a well-developed tectonic foliation sub-parallel to layering, as well as discrete plastic shear zones overprinting the foliation. Layering attitudes are highly variable, as was also noted by Nagel (1979). The rocks have a porphyroclastic texture, outlined by flattened pyroxene grains with tailed recrystallized margins of brown and green pleochroic hornblende indicating deformation under amphibolite facies conditions. The deformed gabbros are cut by small, irregularly shaped stocks of isotropic, fine-grained to pegmatitic gabbros; by variably textured gabbroic veins; and by abundant fine-grained gabbroic to dioritic dikes which have highly variable orientation. This intrusive sequence resembles the high-level gabbros of the plutonic blocks in many respects.

The contact zone with the volcanic rocks is characterized by an increase in the occurrence of dikes, by frequent microgabbroic stocks, and narrow screens of intensely sheared pillowed and massive lavas between intrusive phases. Locally, dike swarms appear to have coalesced into small sheeted dike sections, but a sheeted dike complex is certainly not well developed along the contact zone. Small plugs and sills of microgabbro are found locally, higher within the volcanic succession.

The volcanic rocks (Unit 9) comprise mainly pillow lava with subordinate massive flows and pillow breccia; they are cut by fine-grained diabase dikes. In mildly deformed parts of the sequence, the pillows are small in size, ranging up to 0.5 metre in diameter, and rounded in shape (Plate 3-4-7). They are fined grained to aphanitic and locally vesicular and porphyritic; the original ferromagnesian phenocrysts now occur as chloritic pseudomorphs. Massive flows are up to 2 metres thick and locally show banding outlined by concentrations of amygdules. The rocks are strongly altered to low greenschist facies assemblages with abundant quartz, epidote and chlorite; silicification is intense and widespread. Compositionally the lavas appear to range from basalt to dacite.

The thrust contact between the volcanic rocks and underlying sedimentary rocks of the Hurly Formation is well exposed along the upper eastern slopes of East Liza Creek. In the lavas it is a zone of silicic banded mylonite and phyllonite with well-developed C-S fabrics up to 1 metre thick. At one locality, the thrust is clearly cut by a diorite dike that can be traced over some distance into the underlying sedimentary rocks. Various shear-sense criteria in the mylonites consistently indicate southwest-directed thrusting, identical to the movement pattern of the S_2 serpentinite mylonites which directly overlie the volcanic rocks in the northern part of outcrop area of the East Liza suite. Deformation associated with this thrusting has not been recognized with certainty

Plate 3-4-6. Detail of thrust contact between basal mylonite of serpentinite mélange and underlying gabbro, with steep fine-scale layering, of East Liza igneous suite. Composite fabric in serpentinite consists of an early steeply dipping schistosity (S_1) and a later, mylonitic serpentinite fabric (S_2) which is subparallel to the thrust contact.

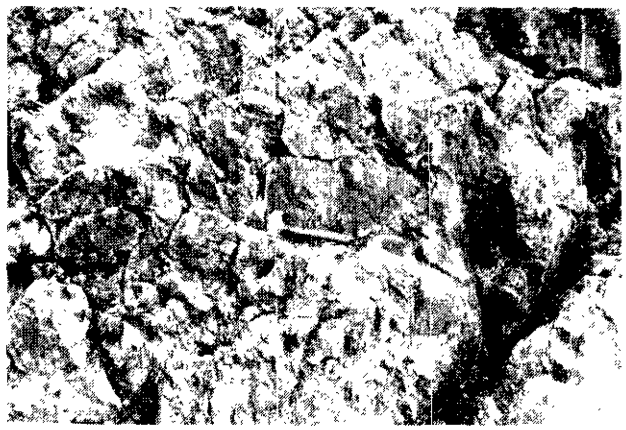


Plate 3-4-7. Mildly deformed pillow lavas of East Liza igneous suite in western part of study area.

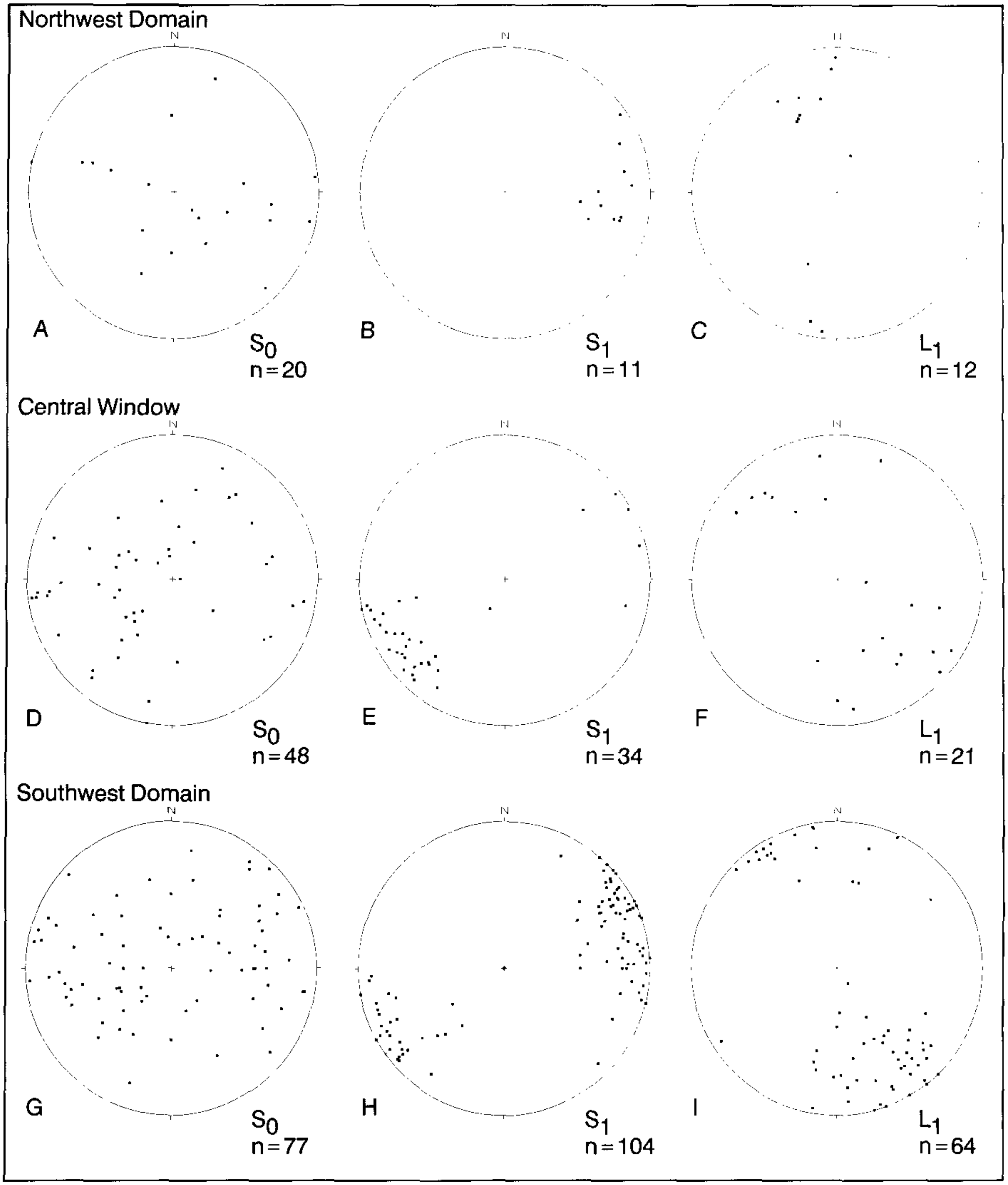


Figure 3-4-3. Orientation patterns of cleavage fold systems in three domains of Hurley Formation: (A-C) northwestern domain, (D-F) northern half-window, (G-I) southwestern domain. A, D, G are plots for poles to bedding: B, E, H are plots for poles to axial planar cleavage; C, F, I are plots of bedding/cleavage intersection lineations and axes of small-scale folds; all plots are in equal area, lower hemisphere projection.

within the volcanic sequence. The presumed thrust contact between gabbros and Hurley Formation is nowhere exposed in the study area. The contact is deformed in macroscopic cleavage folds with associated thrusts. The folding is spectacularly developed in the Hurley footwall (*see* below). It caused widespread cleavage formation with associated flattening of pillows in the volcanic sequence. This cleavage dips steeply to the southwest and obscures many of the original features of the volcanic sequence; it is only locally developed in the gabbros to the south. All structures are cut by a complex extensional fault system that controls much of the present outcrop pattern of the eastern contact of the East Liza suite with the serpentinite mélange (*see* also below).

CADWALLADER GROUP, HURLEY FORMATION (UNIT 10)

This unit comprises a variety of siliciclastic and calcareous sedimentary rocks which, on the basis of lithological correlation, are assigned to the Late Triassic Hurley Formation (Rusmore, 1987). To date, however, no biostratigraphic data are available for the unit in the map area. The most prominent sequence in the unit consists of thin to medium-bedded grey sandstones and laminated grey to black siltstones, which are turbiditic in nature displaying grading as well as convolute and crosslamination. It contains interbedded limestone, chert and pebble conglomerate, which become more abundant towards the stratigraphic base of the unit. Massive, locally fossiliferous limestone and limestone breccia occur as discontinuous lenses up to 5 metres thick. White to grey, massive chert beds intercalated with the siliciclastic rocks range from 0.5 to 3 metres in thickness. Matrix-supported pebble conglomerates contain subrounded clasts of felsic and mafic (sub-)volcanic rocks. The turbidite sequence becomes more calcareous towards its stratigraphic top (Plate 3-4-8), consisting of medium to thick-bedded (up to 1 metre), graded calcarenites, calcareous shales and rare, thin discontinuous limestone beds. The unit is cut by rare, thin dikes ranging in composition from basalt to quartz diorite.

All rocks of the unit are affected by regional folding associated with intense axial planar cleavage development (Plate 3-4-8). The fold system comprises several orders of folds, ranging from small crenulations to macroscopic antiform-synform pairs. Orientation patterns of the fold system are presented in Figure 3-4-3 for three domains in the study area. Folds in the northwestern domain, directly west of the northernmost gabbro blocks in the serpentinite mélange (Figure 3-4-2), define a plane, subcylindrical, steeply inclined system that plunges gently to the north; the folds are close to tight, asymmetric with easterly vergence. The folds in the northern half-window of Hurley Formation (Figure 3-4-2) define a plane, noncylindrical, close to tight system for which fold asymmetry is not well established. The folds are steeply northeasterly inclined and markedly doubly plunging (Figure 3-4-3). Due to severe late extensional faulting, it is not clear whether or not this folding affects the thrust contacts with the overlying serpentinites and volcanic rocks. A penetrative cleavage with identical orientation is observed in the volcanic rocks, but does not appear to affect the S_2 serpentinite mylonites. The fold system in the southwestern domain, along the eastern slope of East Liza Creek, is nonplanar noncylindrical, close to tight; it is steeply inclined to the southwest and plunges mainly to the southeast (Figure 3-4-3). It is markedly asymmetric with east-northeasterly vergence expressed by steeply west-dipping overturned short limbs and associated moderately west-dipping thrusts. the fold and thrust system clearly involves not only the Hurley Formation, but also the overlying East Liza volcanic rocks and S_2 serpentinite mylonites of the mélange. In one small area in the northern part of the domain (Figure 3-4-2), the volcanic rocks and serpentinites define an overturned antiform-synform pair that is cut on its western side by an easterly verging thrust system comprising thin sheets of volcanic and sedimentary rocks. The thrusts are outlined by thin phyllitic C-S mylonite zones consistently showing north-northeast-directed movement. The fold and thrust system effectively terminates against a late, normal fault in the east and is cut by numerous small extensional faults which are not shown on the map.

Plate 3-4-8. Limb domain of mesoscopic cleavage fold in thin-bedded calcareous shales of Hurley Formation, Cadwallader Group. This fold is a parasitic structure in the core of a southeast-plunging antiform. Note angular relationship between bedding and axial planar cleavage.

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