New geological investigations of the Early Jurassic Polaris ultramafic-mafic Alaskan-type intrusion, north-central British Columbia

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Recommended citation: Nott, J., Milidragovic, D., Nixon, G.T., and Scoates, J.S., 2020. New geological investigations of the Early Jurassic Polaris ultramafic-mafic Alaskan-type intrusion, north-central British Columbia. In: Geological Fieldwork 2019, British Columbia Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey Paper 2020-01, pp. 59-76.

Abstract

The Polaris Alaskan-type ultramafic-mafic intrusion in north-central British Columbia is an exceptionally well-exposed, north-northwesterly trending sill-like body 14 km long by 3 km across. Rock types are distributed asymmetrically, with dunite prevalent in the east, wehrlite, clinopyroxenite, and zones of chaotically intermingled ultramafic cumulates in central areas, and gabbro-diorite to hornblende clinopyroxenite in the west. Key observations are the variable nature of lithological contacts, complex dike and sill emplacement relationships, evidence for magmatic disruption of ultramafic cumulates, and eastward-directed thrusting of the entire intrusion atop contact aureole rocks in the east. Sharp to diffuse contacts suggest mingling and melt infiltration of previously formed cumulates of olivine clinopyroxenite, wehrlite, and dunite, and localized chaotically intermingled zones incorporating all these rock types. Disrupted chromitite layers hosted primarily by dunite occur as schlieren, folded chromitite layers and isolated blocks containing thin chromitite horizons, features interpreted as remobilized cumulates. Ni-Cu-platinum group element sulphides hosted by clinopyroxenite are mainly found in the western part of the intrusion. Ongoing research aims to establish the temporal and magmatic evolution of the intrusion with implications for the nature and timing of sulphide mineralization.

Keywords: Alaskan-type, ultramafic-mafic intrusion, Polaris intrusion, Lay Range, Quesnellia, Ni-Cu sulphides, platinum-group elements

1. Introduction

Magmatic nickel-copper-platinum group element (Ni-Cu-PGE) deposits at convergent margins are gaining global importance as an economic resource (e.g., Xiarihamu, Song et al., 2016; Aguablanca, Piña, 2019), yet remain poorly understood and underexplored (Nixon et al., 2015; Manor et al., 2016, 2017). The Cordillera of British Columbia and Alaska hosts a number of ultramafic-mafic bodies with Ni-Cu-PGE-mineralization (e.g., Duke Island, Tulameen, Turnagain, Polaris, Giant Mascot; Fig. 1) many of which exhibit broad lithological zonation from a dunite core to a pyroxenite/hornblendite or gabbro-diorite margin. The (Ural-) Alaskan-type or 'concentrically zoned' ultramafic-mafic intrusions described in the literature (e.g., Taylor, 1967; Irvine, 1974a, 1976; Himmelberg and Loney, 1995) form a distinct subclass of convergent margin intrusive bodies distinguished by the predominance of olivine, clinopyroxene, and hornblende±plagioclase, and importantly, by the absence of orthopyroxene (Nixon et al., 2015). In the IUGS classification scheme for ultramafic rocks (Le Maitre, 1989), Alaskan-type rocks are confined to the olivine-clinopyroxene join with variable amounts of hornblende (Fig. 2).

Several Alaskan-type intrusions in British Columbia with known Ni-Cu-PGE sulphide mineralization are being investigated as part of the Geological Survey of Canada's Targeted Geoscience Initiative 5 Program (TGI-5). The principal objective of the research is to establish the nature and timing of Ni-Cu-PGE sulphide mineralization with respect to the temporal and magmatic evolution of the intrusions to develop new models to guide mineral exploration (e.g., Giant Mascot intrusion, Manor et al., 2016, 2017; Turnagain intrusion, Jackson-Brown, 2017; Nixon et al., 2019a). The present study focusses on the Early Jurassic Polaris ultramafic-mafic intrusion, a superbly exposed Alaskan-type body in north-central British Columbia. The intrusion hosts sparsely platiniferous chromitites in dunite, and poorly documented magmatic Ni-Cu-PGE sulphide mineralization (Nixon et al., 1997). Herein, we present the preliminary results of a two week reconnaissance in 2018 and six weeks of detailed mapping in 2019. We describe the main rock types in the intrusion and their contact relationships, the zonation of the intrusion, the distribution of magmatic Ni-Cu-PGE sulphide occurrences, and intrusion-country rock relationships.

2. Previous work

Roots (1954) provided the first detailed descriptions of the Polaris intrusion. This work was followed by petrological studies and internal mapping by Foster (1974) and Irvine

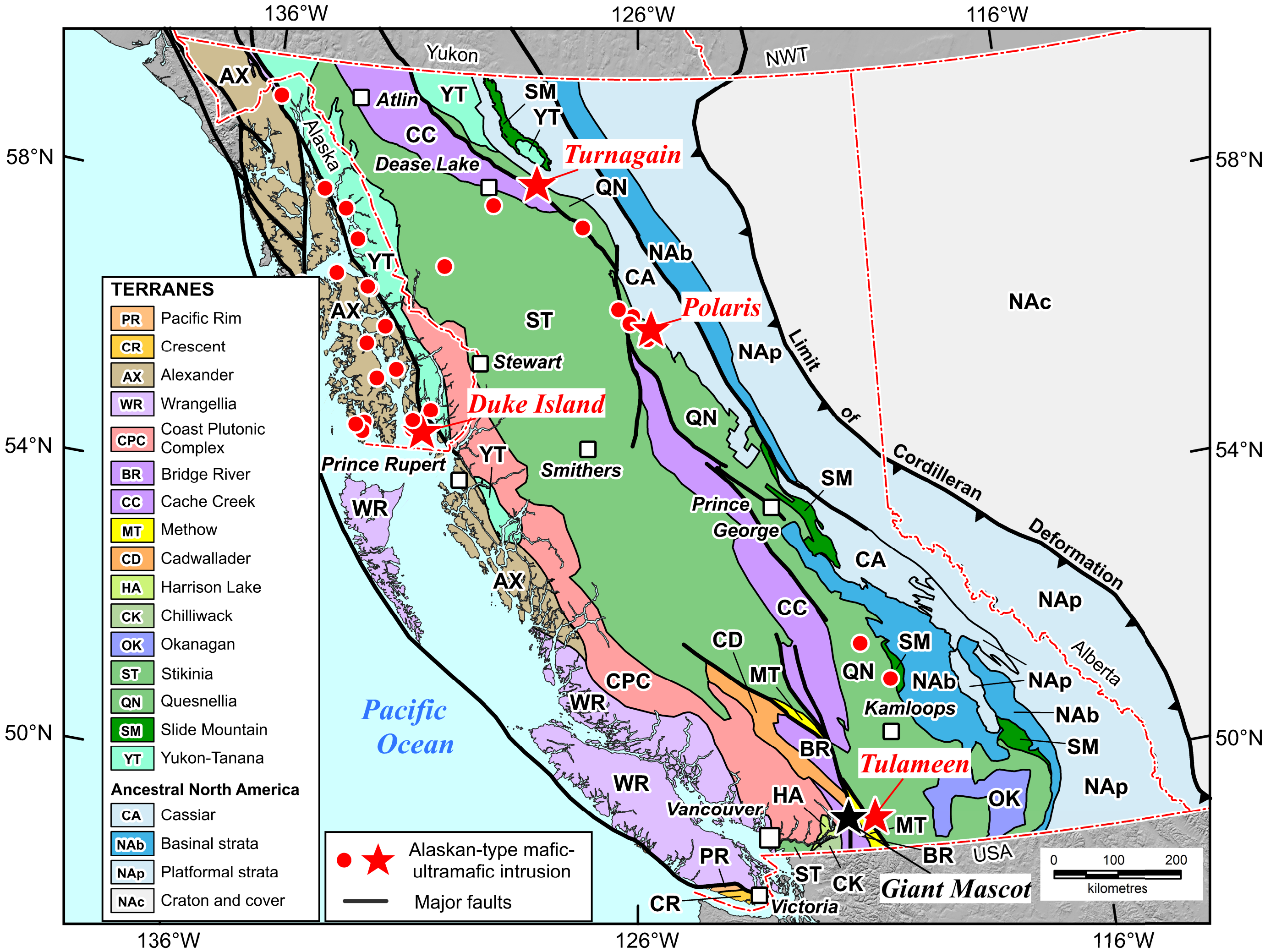

Fig. 1. Location of the Polaris, other Alaskan-type intrusions, and the Giant Mascot orthopyroxene-rich ultramafic-mafic intrusion with respect to terranes of the Canadian Cordillera. Adapted from Nelson et al. (2013) and Nixon et al. (2019).

(1974b, 1976), who recognized the Alaskan-type affinity of the intrusion, and by Nixon et al. (1997) who published detailed geological maps and PGE analyses. The regional context of the intrusion was mapped at a 1:50,000 scale by Ferri et al. (2001). A multi-grain U-Pb zircon date of 186 ±2 Ma (Early Jurassic) was reported by Nixon et al. (1997) from a quartz-hornblende-plagioclase pegmatite in hornblendite near the northwestern margin of the intrusion (Fig. 3). This sample was reprocessed for single-grain CA-TIMS analysis and yielded a more precise date of 186.26 ±0.14 Ma, interpreted as the crystallization age of the pegmatite (Nixon et al., 2019b).

3. Regional geology

The Polaris ultramafic-mafic intrusion (56°30'N, 125°40'W) is in the Lay Range of the Omineca Mountains in north-central British Columbia, approximately 200 km northeast of Smithers (Fig. 1). The intrusion was emplaced into late Paleozoic (Mississippian-Permian) metasedimentary and metavolcanic rocks of the Lay Range assemblage, which forms the substrate for early Mesozoic, arc-derived volcanosedimentary strata of Quesnellia. During the late Paleozoic to early Mesozoic, Quesnellia lay outboard of ancestral North America, separated from the continental margin by the Slide Mountain ocean, which developed as a back-arc basin (e.g., Nelson et al., 2013). At the latitude of Polaris, the Slide Mountain terrane is absent or structurally excised (Ferri, 1997; Ferri et al., 2001), and Quesnellia is in thrust contact with Late Devonian to Permian rocks of the continental margin. Late Devonian to Permian slate, argillite, tuff, and sandstone of the Big Creek group form the uppermost part of the pericratonic Cassiar terrane, a displaced fragment of the Neoproterozoic to Paleozoic ancestral North American margin (Ferri, 1997; Nixon et al., 1997; Ferri et al., 2001; Fig. 3).

Polaris is the largest of several ultramafic-mafic bodies of Alaskan-type affinity that intrude Quesnellia (Irvine, 1976; Nixon et al., 1997). Emplacement of the Polaris intrusion was coeval with the accretion of major arc terranes in the northern Cordillera (ca. 185-186 Ma, Early Jurassic; Nixon et al.,

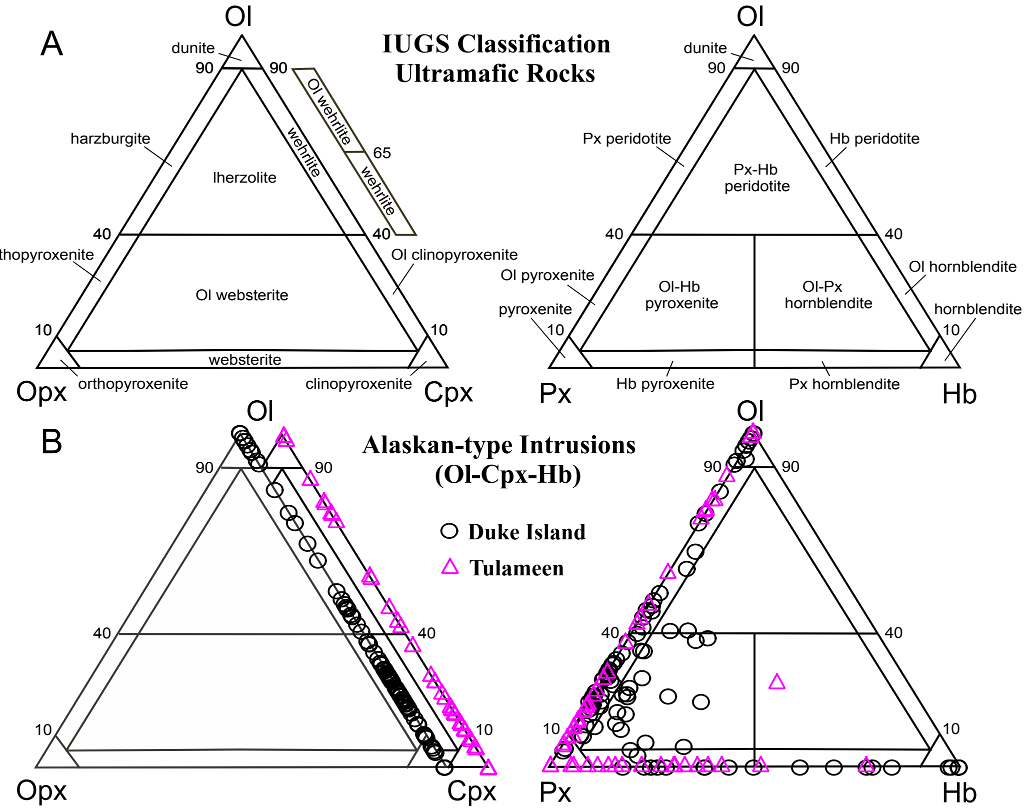

Fig. 2. **a)** IUGS classification of ultramafic rocks (Le Maitre, 1989). **b)** Modal analyses for typical ultramafic rocks in the Duke Island (Irvine, 1959, 1974) and Tulameen (Findlay, 1963) Alaskan-type intrusions showing the characteristic absence of orthopyroxene. Abbreviations: Ol, olivine; Cpx, clinopyroxene; Opx, orthopyroxene; Px, pyroxene (clinopyroxene+orthopyroxene); Hb, hornblende. Adapted from Nixon et al. (2015).

2019a, b), and the thermal aureole was still hot and capable of ductile deformation during thrust emplacement onto the continental margin (Nixon et al., 1997).

4. Geology of the Polaris intrusion

The Polaris intrusion is one of the best exposed Alaskan-type ultramafic-mafic bodies in the Canadian Cordillera, second in size only to the Tulameen intrusion in south-central British Columbia (Nixon et al., 1997; Fig. 1). The Polaris intrusion is a sill-like body (Nixon et al., 1997) that is exposed across an area 14 km long by 3 km across (45 km^2). It is hosted entirely within moderately westward-dipping (40-50°), mafic-intermediate volcanic breccias, flows, and sedimentary strata of the Paleozoic Lay Range assemblage (Roots, 1954). The intrusion consists of asymmetrically distributed ultramafic rocks, which predominate in the eastern part of the intrusion, and hornblende-bearing gabbroic-dioritic and pyroxenitic lithologies in the west (Fig. 3). The principal rock types include: dunite (±chromitite), wehrlite, olivine clinopyroxenite, clinopyroxenite, hornblende-clinopyroxenite, hornblendite, and gabbro-diorite. Accessory minerals such as apatite, titanite, and zircon comprise <2% of the more evolved mafic lithologies. Orthomagmatic sulphides (pyrrhotite, pentlandite, chalcopyrite) are locally encountered in clinopyroxene- and hornblende-rich rocks.

The metamorphic contact aureole in the volcanosedimentary host rocks is upper greenschist to lower amphibolite facies. The aureole locally exhibits an amphibole lineation and foliation. Andalusite has been observed in the southern and eastern contact aureole, constraining the depth of emplacement to less than 12 km (Nixon et al., 1997). Along parts of its eastern margin, the Polaris intrusion is in thrust contact with variably foliated to non-foliated gabbro-diorite, and locally hornfelsed volcanosedimentary rocks of the Big Creek group (Fig. 4). Recent field mapping and integration of aeromagnetic and radiometric survey modelling (CGG Canada Services Ltd., 2018) has enabled refinement of lithological boundaries, especially near the eastern thrust margin (Fig. 3).

4.1. Lithological units

The Polaris intrusion contains all the rock types characteristic of Alaskan-type ultramafic-mafic bodies, including dunite, wehrlite, clinopyroxenite, hornblendite, gabbro-diorite, and felsic pegmatite. In contrast to examples where Alaskan-type intrusions are concentrically zoned (e.g., Tulameen; Nixon, 2018), the distribution of rock types is distinctly asymmetric at Polaris. Lithological contacts are sharp to locally gradational, in cases diffuse (Fig. 5). Variations in grain size and crystal habit occur on cm to m scales.

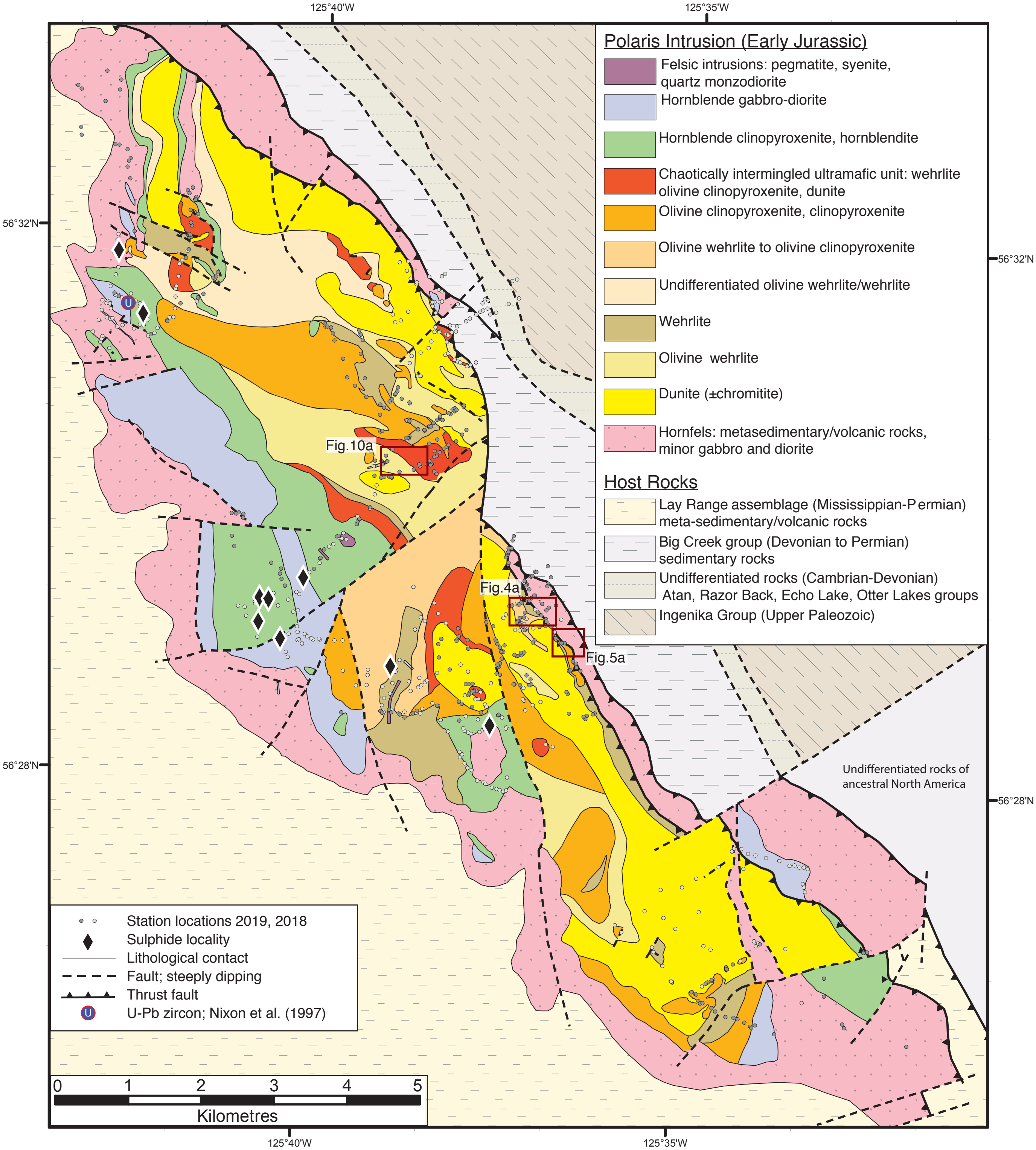

Fig. 3. Generalized geology of the Polaris Alaskan-type ultramafic-mafic intrusion (modified from Nixon et al., 1997) showing regional geology, contact relationships, and intrusive rock types. Locations of photographs in Figures 4a, 5a, 10a are shown.

4.1.1. Dunite

Dunite is generally confined to the eastern part of the intrusion (Fig. 3). Weathered dunite is yellow-brown and displays smooth surfaces with cm-thick weathering rinds; fresh dunite appears dark grey (Fig. 6). Interlocking olivine crystals (<2 mm) exhibit adcumulate textures (i.e., <7 vol.%, of interstitial minerals); dunite with heteradcumulate textures and clinopyroxene oikocrysts occurs locally. All dunite samples contain trace amounts of disseminated, fine-grained, subhedral to euhedral chromite. Dunite is generally weakly serpentinized,

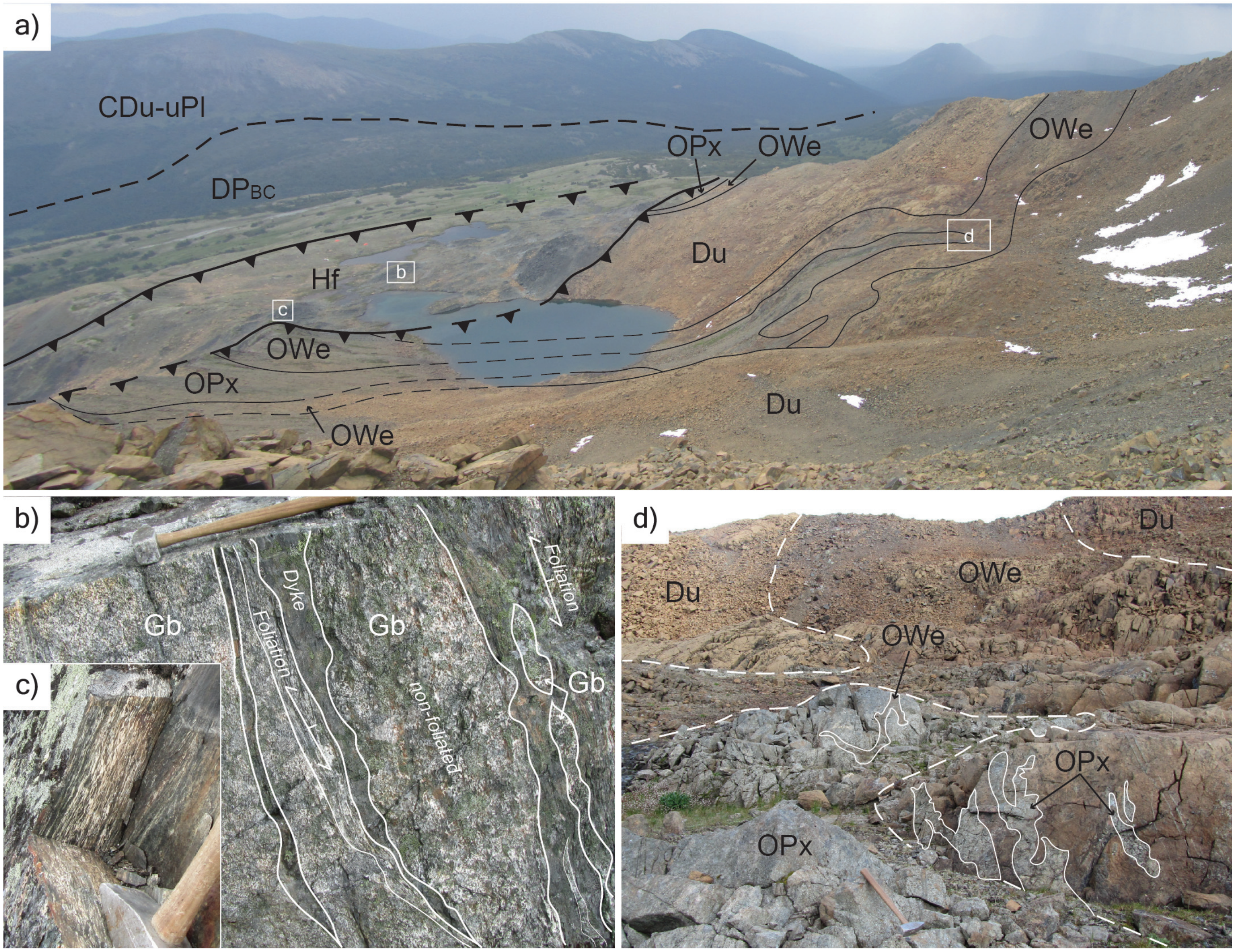

Fig. 4. Contact relationships and internal features at the eastern margin of the Polaris intrusion. **a)** View looking east-southeast showing thrust fault contacts (solid lines with teeth) between ultramafic rocks in the foreground and the metamorphic aureole (Hf), metasedimentary rocks of the Big Creek group (DP_{BC}; Devonian to Permian), and undifferentiated Cambrian-Devonian and upper Paleozoic strata (CDu-uPl) of the ancestral North American continental margin. Polaris ultramafic units include dunite (Du), olivine wehrlite (OWe), and olivine clinopyroxenite (OPx). Locations of photographs in panels b, c, and d are indicated. **b)** Heterogeneously foliated gabbro-diorite (Gb) and mafic dikes forming boudins; Big Creek group. View looking south. **c)** Mylonitic gabbro with fabrics of possible kinematic significance; these fabrics are typically developed at the thrust contact between ultramafic lithologies and host rocks in the eastern contact aureole. View looking north. **d)** Inclusions of olivine wehrlite (OWe) in olivine clinopyroxenite (OPx), and olivine wehrlite in olivine clinopyroxenite, between lobes of dunite (Du). Note the gradational contact between dunite and olivine wehrlite. Contacts: observed, solid line; inferred, dashed line.

except in shear zones where serpentinization is moderate to complete. In several areas, dunite contains a weak foliation, defined by laterally extensive micro-veinlets (<0.5 mm wide) of serpentine group minerals that border local shear zones.

Fine-grained, dunite dikes (up to 30 cm wide), with adcumulate to heteradcumulate textures involving clinopyroxene, intrude the main dunite unit and are only distinguishable where they cut dunite containing mineralogically distinctive features, such as chromitite laminae and/or olivine wehrlite, wehrlite, or olivine clinopyroxenite dikes (e.g., Fig. 7a). Dunite dikes that cross-cut olivine wehrlite/wehrlite and olivine clinopyroxenite commonly exhibit irregular contacts that appear to indicate ductile rheology. Dunite containing rare Mg-Fe mica (phlogopite?) displays pitted surfaces due to recessively weathered mica and occurs near contacts with olivine clinopyroxenite and wehrlite; it is generally concentrated in the eastern parts of the intrusion. Dunite near olivine clinopyroxenite (section 4.1.4.) and chaotically intermingled units (section 4.1.5.) is gradational with olivine wehrlite and wehrlite.

4.1.2. Chromitite

Chromitite occurs in dunite, and less commonly in olivine wehrlite and wehrlite, as m-scale schlieren of massive chromite, and as disrupted blocks of variably deformed chromite interlayered with olivine (Fig. 7). Chromitite occurs as both massive and nearly monomineralic chromite layers, and

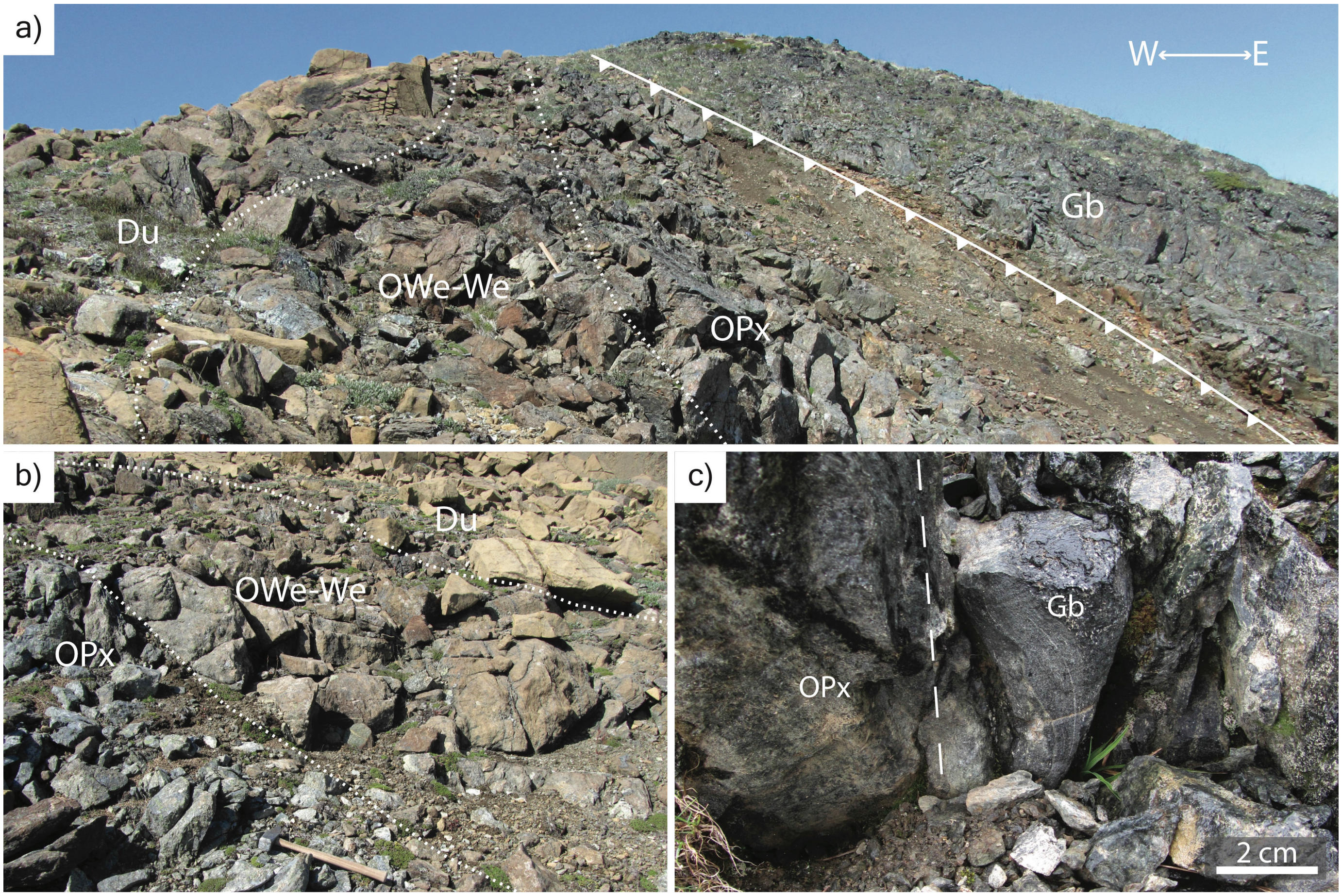

Fig. 5. Contact relationships in the eastern part of the Polaris intrusion. **a)** Footwall gabbro (Gb) in thrust contact with olivine clinopyroxenite (OPx) that grades, from east to west, into olivine wehrlite to wehrlite (OWe-We) and dunite (Du). View looking north. **b)** M-scale gradational contacts of olivine clinopyroxenite, olivine wehrlite to wehrlite, and dunite. **c)** Undeformed coarse-grained (≤5 mm) olivine clinopyroxenite in thrust contact with mylonitic gabbro in the footwall. Contacts: gradational, dotted line; observed/approximate, solid/dashed line.

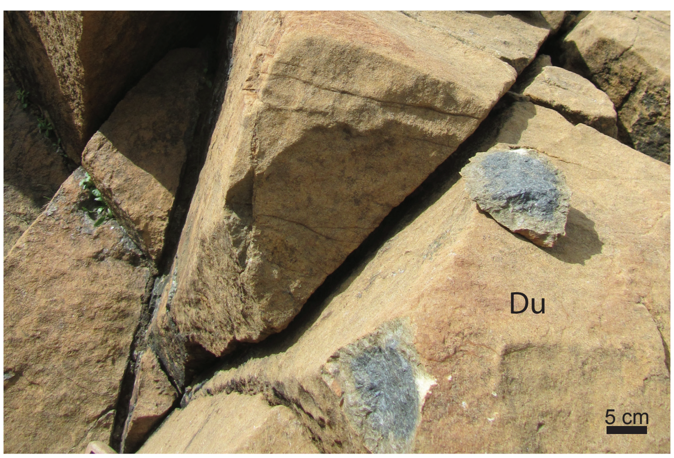

Fig. 6. Typical dunite; fine- to medium-grained (<1-2 mm) adcumulate olivine±minor clinopyroxene. Brown to yellow-brown weathered surface and 1-2 cm thick weathering rind; dark grey fresh surface.

as diffuse layers intergrown with olivine. Typically, chromitite schlieren display features that are consistent with remobilization of previously formed crystal cumulates (Figs. 7a, b, d, e). Chromitite is comparatively rare in wehrlite and is sparsely entrained in wehrlitic dikes.

4.1.3. Olivine wehrlite and wehrlite

Wehrlite forms extensive outcrops in the central and northern parts of the Polaris intrusion. It weathers brown to orange-brown, with rough surfaces from differential weathering of clinopyroxene relative to olivine (Fig. 8b). Wehrlite, like dunite, locally displays pitted surfaces from weathering of phlogopite (Fig. 8c). For mapping purposes, Nixon et al. (1997) distinguished 'olivine wehrlite' (olivine-rich rocks with 10-35% modal clinopyroxene) from wehrlite (35-60% modal clinopyroxene; Fig. 2). Texturally distinct varieties of wehrlite, differentiated by variation in the modal abundance and grain-size (1 mm-10 cm) of clinopyroxene are recognized on scales of 1 to 100s of m. Idiomorphic clinopyroxene (from <1 mm to 10s of cm) occurs in wehrlite (Figs. 8a, b, d). In contrast, olivine wehrlite typically displays a poikilitic texture where clinopyroxene forms irregular (5 mm to 6 cm) oikocrysts enclosing olivine (Fig. 8e). Locally, clustering and grain-size variation of clinopyroxene increases close to contacts with chaotic intermingled units (intermingled olivine clinopyroxenite, wehrlite, and dunite; see section 4.1.5.). Throughout the intrusion, wehrlite occurs as an intermediate lithology with gradational boundaries to olivine clinopyroxenite,

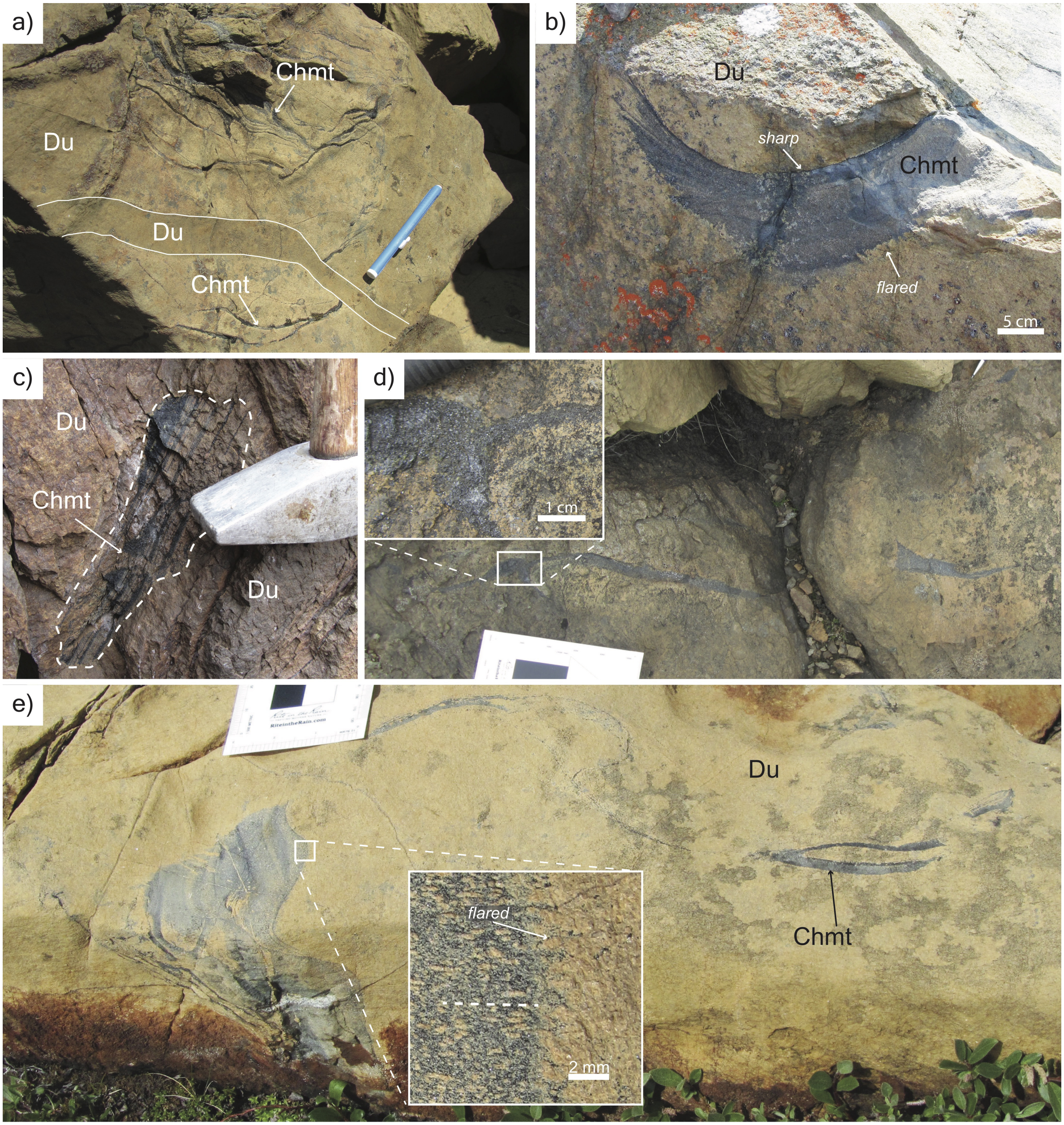

Fig. 7. Chromitite morphologies in the Polaris intrusion. **a)** Block-like mass containing thin (<1 cm thick) chromitite (Chmt) schlieren in dunite (Du). Chromite layers are sub-parallel, slightly crenulated, and locally bifurcate. Dunite dike (solid line) cuts bifurcated chromitite layer. **b)** Bent chromitite schlieren, approximately 15 x 30 x 80 cm in dunite. The upper chromitite-dunite contact is sharp, the lower contact is diffuse and displays cuspate-lobate irregularities. **c)** Chromitite block containing planar chromite layers (2-30 mm thick) in dunite. **d)** Cm-wide discontinuous slightly distorted chromitite layer. Inset shows diffuse boundaries with dunite. **e)** Layered, olivine-rich chromitite schlieren in dunite. Crystal-scale foliation in the chromitite is defined by <0.5 x 1 mm elongated olivine clusters (dashed line on inset).

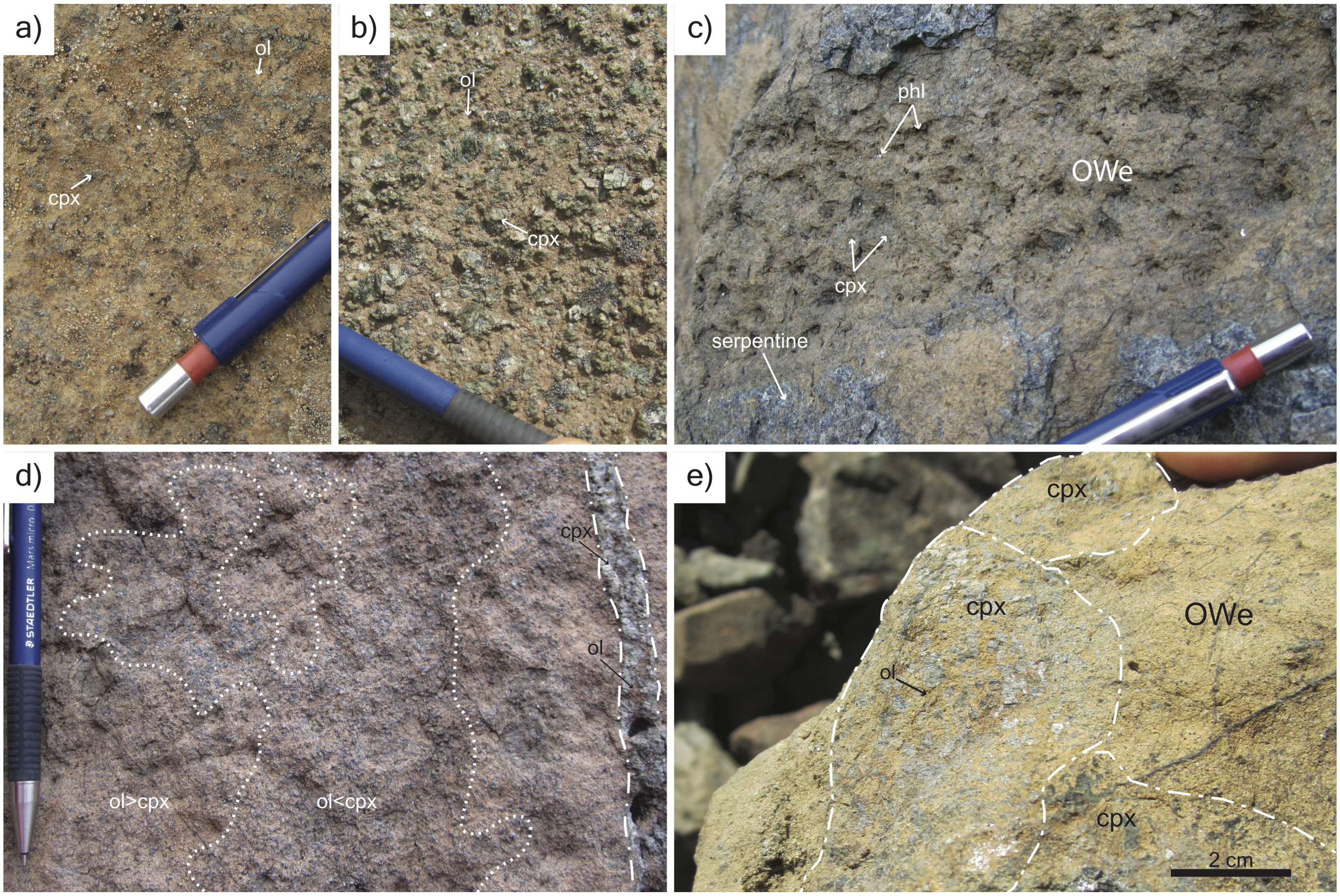

Fig. 8. Textural variations of wehrlite in the Polaris intrusion. **a)** Wehrlite with fine- to medium-grained (<1-2 mm), equant idiomorphic clinopyroxene (cpx) intergrown with olivine crystals. Clinopyroxene forms crystal clusters interstitial to olivine. **b)** Very coarse-grained (~1 cm) clinopyroxene-rich wehrlite in a fine-grained (<1 mm) groundmass of olivine (ol). **c)** Phlogopite(phl)-bearing olivine wehrlite (OWe) displaying characteristic pitting due to recessively weathered phlogopite. A thin serpentinized surface (dark grey-blue) is locally present along joints. **d)** Fine-grained wehrlite with cm-scale modal variations of clinopyroxene and olivine. Dotted line delineates diffusely bounded zones with variable modal clinopyroxene. Along the right side of the image is a centimetre-wide olivine clinopyroxenite veinlet with diffuse boundaries (dash-dot lines). **e)** Poikilitic clinopyroxene (cpx) in olivine wehrlite (OWe). The large oikocryst in the center of the image is ~6 cm x 4 cm and encloses <4 mm diameter patches of fine-grained olivine (ol) crystals.

chaotic intermingled units, and dunite. Coarse to pegmatitic olivine clinopyroxenite/wehrlite dikes, with diffuse contacts, are also observed in wehrlite near chaotic intermingled units.

4.1.4. Olivine clinopyroxenite and clinopyroxenite

Olivine clinopyroxenite and clinopyroxenite are generally distributed along the central axis of the intrusion and at the southern and eastern margins. Olivine clinopyroxenite/clinopyroxenite weathers light to pale green to greenish-grey and has an increasingly mottled rusty-brown appearance with increasing olivine content (Figs. 9a, b). Fresh surfaces are dark greenish-grey. Olivine clinopyroxenite comprises <40% olivine and >60% clinopyroxene, whereas clinopyroxenite has <10% olivine and >90% clinopyroxene (Fig. 2). Mappable units of olivine clinopyroxenite show considerable heterogeneity at the outcrop scale with a tendency for olivine clinopyroxenite to be intermingled with, and contain significant quantities of, dm-scale wehrlite/dunite enclaves with both sharp and gradational boundaries (e.g., Figs. 9a, c). Minor amounts of hornblende and magnetite occur interstitially, and magmatic sulphides (mainly pyrrhotite and chalcopyrite) are locally present. Clinopyroxene crystals are typically 2-10 mm in diameter, fresh, and idiomorphic, with modal abundances varying on scales of 10s of cm.

Pegmatitic dikes of olivine clinopyroxenite and clinopyroxenite have sharp (Fig. 9b) to gradational, in cases diffuse, boundaries (Figs. 10b; 11c, d) throughout the intrusion and they cut all ultramafic rock types. Where close to or in large outcrops of olivine clinopyroxenite or chaotic intermingled units, clinopyroxenite dikes commonly have pegmatitic to diffuse margins, and may incorporate pods of host dunite and/or wehrlite. Late, coarse-grained to pegmatitic olivine clinopyroxenite and clinopyroxenite (±phlogopite) dikes (<2 m wide) have sharp contacts and locally exhibit prismatic clinopyroxene crystals oriented perpendicular to dike contacts.

Bright olive-green, granular and equant (1 mm), anhedral

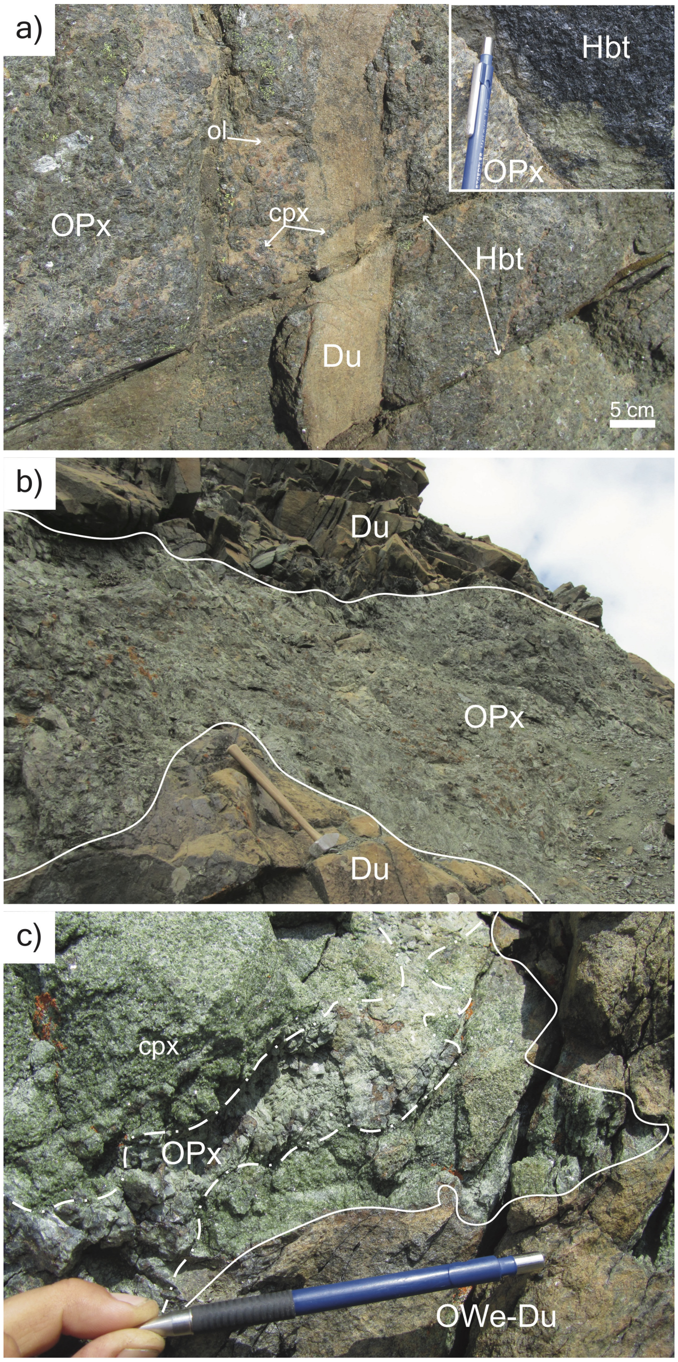

Fig. 9. Textural variations of olivine clinopyroxenite (OPx) in the Polaris intrusion. **a)** Olivine clinopyroxenite cut by fine-grained dunite dike, in turn cut by thin (<10 cm wide) magnetite-bearing hornblendite (Hbt) dikelets. Inset shows joint surface of fine- to medium-grained (<2 mm) magnetite-bearing hornblendite. **b)** M-scale pegmatitic olivine clinopyroxenite dike in sharp contact with dunite. Clinopyroxene crystals are <10 cm in diameter and enclose pods of fine- to medium-grained (<2 mm) olivine crystals. **c)** Granular, equant, anhedral crystals (<1 mm) of bright green clinopyroxene (cpx) intergrown with coarse-grained (2-5 mm) olivine clinopyroxenite (OPx) in dunite-olivine wehrlite (OWe-Du). Contacts: sharp, solid line; diffuse, dot-dash line.

to idiomorphic adcumulate clinopyroxenite (Fig. 9c) crops out in the northern and northeastern parts of the intrusion. This distinct clinopyroxenite occurs in contact with olivine clinopyroxenite and as xenoliths forming deformed pods in dunite and wehrlite. The clinopyroxenite is also intermingled and/or entrained as boudins (up to 8 m long) in a ductile shear zone enclosing olivine clinopyroxenite and phlogopite-bearing wehrlite/dunite.

4.1.5. Chaotically intermingled ultramafic unit

The chaotically intermingled unit is defined by intermingled olivine clinopyroxenite, wehrlite, and dunite on the dm to m scale. This unit is most common near the margins of clinopyroxenite and wehrlite, and less commonly dunite (Fig. 10a). The best examples of chaotically intermingled units are in the central part of the intrusion (Fig. 3), where they include irregular masses and dikes of coarse to pegmatitic (olivine) clinopyroxenite in dunite and wehrlite (Figs. 10b; 11c). Clinopyroxenite is locally cut by dunite or olivine wehrlite/wehrlite dikes (Fig. 10e). Lithological contacts in the intermingled units vary from sharp to gradational and may be diffuse (Figs. 10b-e; 11a-d). Clinopyroxenite and wehrlite incorporate interstitial (1-10 cm) irregular and embayed pods of dunite-wehrlite (Figs. 10b, c, e; 11c, d). Conversely, enclaves of olivine clinopyroxenite occur within, or are cut by, fine- to medium-grained, highly irregular adcumulate dunite dikes (Figs. 10d, e; 11a, b, d). Magmatic breccias (Figs. 12a-c) comprise subangular to subrounded dm-scale tabular blocks of dunite and wehrlite with diffuse to sharp boundaries set in a coarse-grained matrix of olivine clinopyroxenite to wehrlite (±phlogopite±hornblende).

4.1.6. Hornblendite and hornblende clinopyroxenite

Hornblende-bearing clinopyroxenite is predominantly in the northwestern and western parts of the intrusion and less commonly in the central and southern parts (Fig. 3). Hornblende clinopyroxenite and hornblendite weather dark greenish-black; the presence of saussuritized interstitial feldspar is indicated by irregular white to cream-coloured blebs. Hornblendite and hornblende clinopyroxenite are commonly gradational on a hand sample scale; consequently, the two rock types are not distinguishable at the map scale. Locally, hornblende clinopyroxenite has a well-developed mineral lineation defined by the orientation of elongate hornblende crystals. Magmatic layering within m-scale masses of hornblendite occurs in the northwestern parts of the intrusion and is defined by crystal size gradation and alignment, and by an interstitial feldspathic fabric. Clinopyroxene (<1 cm) is typically euhedral; hornblende forms euhedral prisms up to 10 cm long (Figs. 13a-e). Accessory minerals include sulphides, magnetite, apatite, titanite, phlogopite, and zircon. Significant concentrations of magnetite occur in magnetite-hornblendite layers and dikes (Fig. 13d).

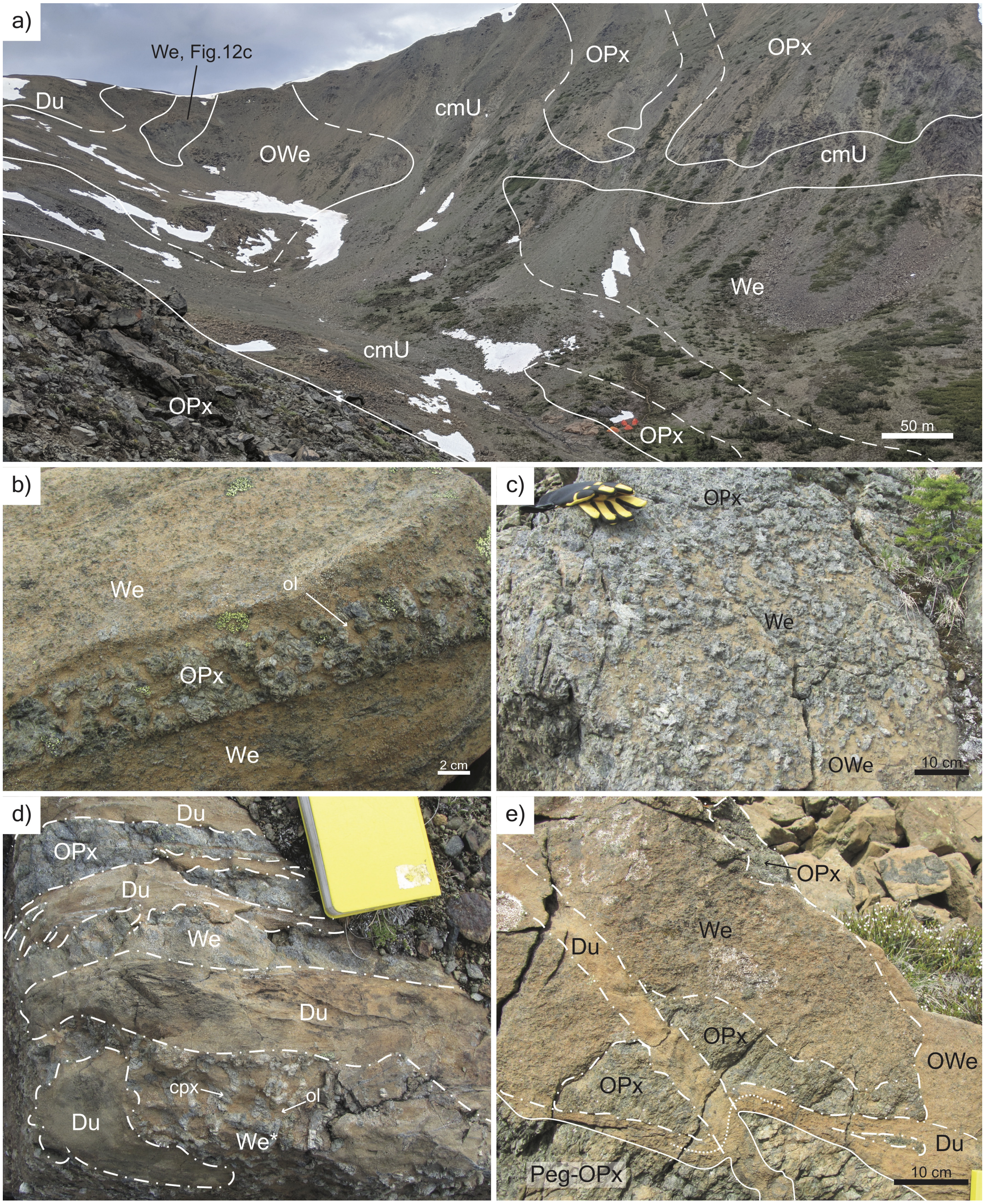

Fig. 10. Textural and lithological relationships in the chaotic intermingled units of the Polaris intrusion. **a)** View looking west (see Fig. 3 for location) illustrating the typical irregular contacts between a chaotic intermingled unit (cmU) and olivine clinopyroxenite (OPx), olivine wehrlite (OWe), wehrlite (We), and dunite (Du). Location of photograph in Fig. 12c is shown. Note orange tents for scale along floor of valley. Contacts: observed, solid line; approximate, dashed line. **b)** Olivine clinopyroxenite (OPx) dike with pegmatitic (1-2 cm) clinopyroxene and fine-grained olivine-rich pods (ol) cutting wehrlite; note diffuse contacts. Wehrlite has 2-5 mm clusters of clinopyroxene crystals (<2 mm) that define modal variation at the centimetre scale. **c)** Subtle modal gradation of pegmatitic (1-4 cm) clinopyroxene and medium-grained (~2 mm) olivine in olivine clinopyroxenite (OPx), wehrlite (We), and olivine wehrlite (OWe). **d)** Interlayered fine-grained dunite, olivine clinopyroxenite, wehrlite, and a distinctive rock with a 'honeycomb' texture of fine-grained olivine pods with coarse (~2 cm) interstitial clinopyroxene (We*). **e)** Complex relationships among dunite (Du), olivine wehrlite (OWe), wehrlite (We), and locally pegmatitic (Peg-OPx) olivine clinopyroxenite (OPx). Offset dunite dike delineated by fine-dashed line. Diffuse contacts, dot-dash line; sharp contacts, solid line.

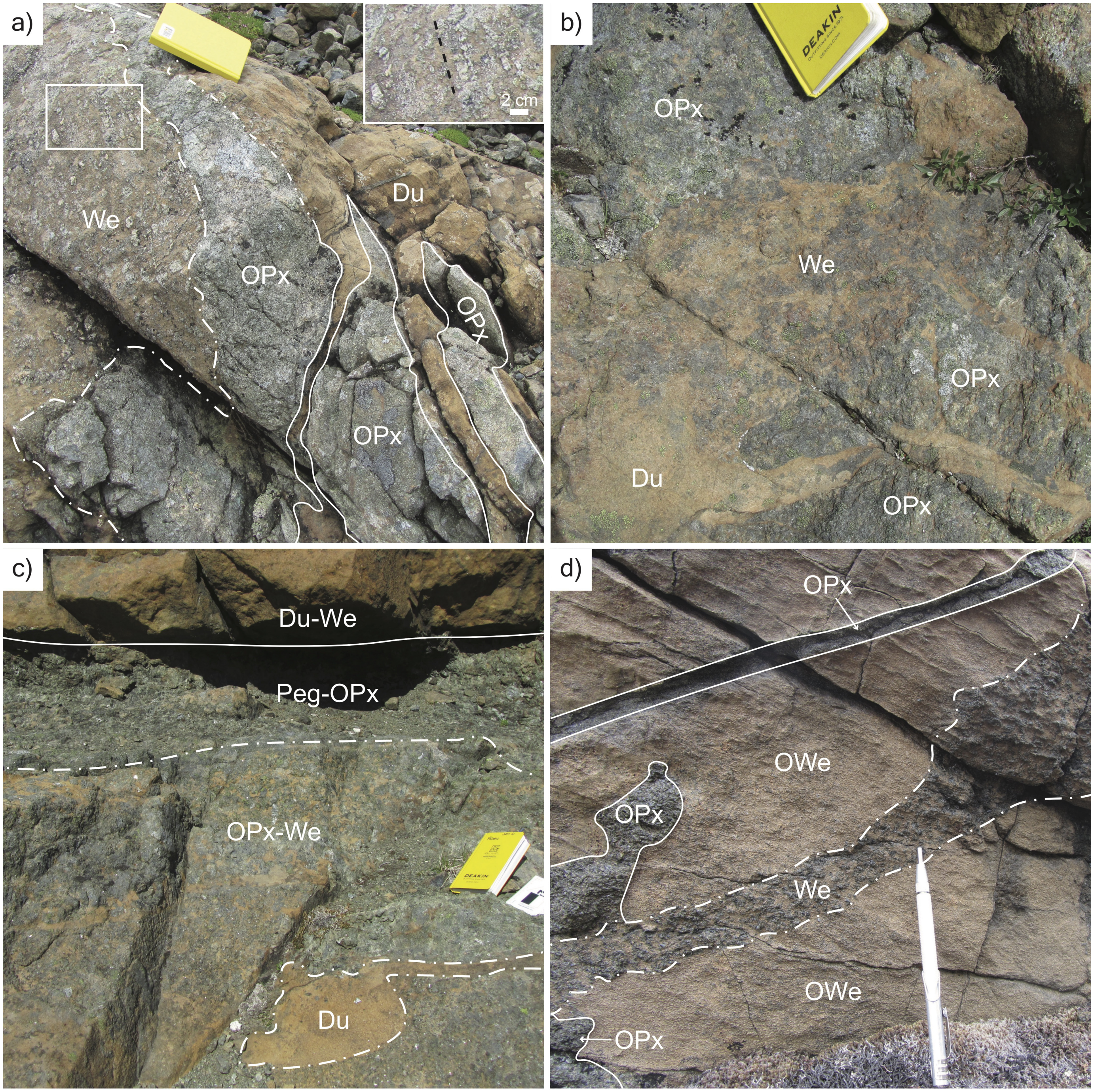

Fig. 11. Representative textures and lithological relationships in chaotic intermingled units (cmU) of the Polaris intrusion. **a)** Coarse-grained olivine clinopyroxenite (OPx) blocks in wehrlite (We), cut by fine-grained dunite dikes (Du). Inset illustrates alignment (dashed line) of subhedral to euhedral clinopyroxene crystals (3-4 cm) in wehrlite. **b)** Heterogeneous zone consisting of dunite (Du) showing gradational boundaries with wehrlite (We) and diffuse to sharp boundary with blocks of olivine clinopyroxenite (OPx). **c)** Pegmatitic (3-10 cm) phlogopite-bearing olivine clinopyroxenite dike (Peg-OPx), with clinopyroxene crystals enclosing centimetre-scale olivine-rich pods. Note the sharp contact between the pegmatite dike and the dunite to wehrlite (Du-We), and the diffuse contact between the dike and coarse-grained olivine clinopyroxenite-wehrlite (OPx-We). The olivine clinopyroxenite-wehrlite contains pods of fine-grained (<1 mm) dunite. **d)** Olivine wehrlite (OWe) with coarse-grained olivine clinopyroxenite (OPx) cut by coarse-grained (<5 mm) clinopyroxene wehrlite (We) with diffuse contacts. Clinopyroxene clusters in wehrlite are ~15 mm and olivine-rich pods have similar textures (equigranular) and grain size as host. Contacts: sharp, solid line; diffuse, dot-dash line.

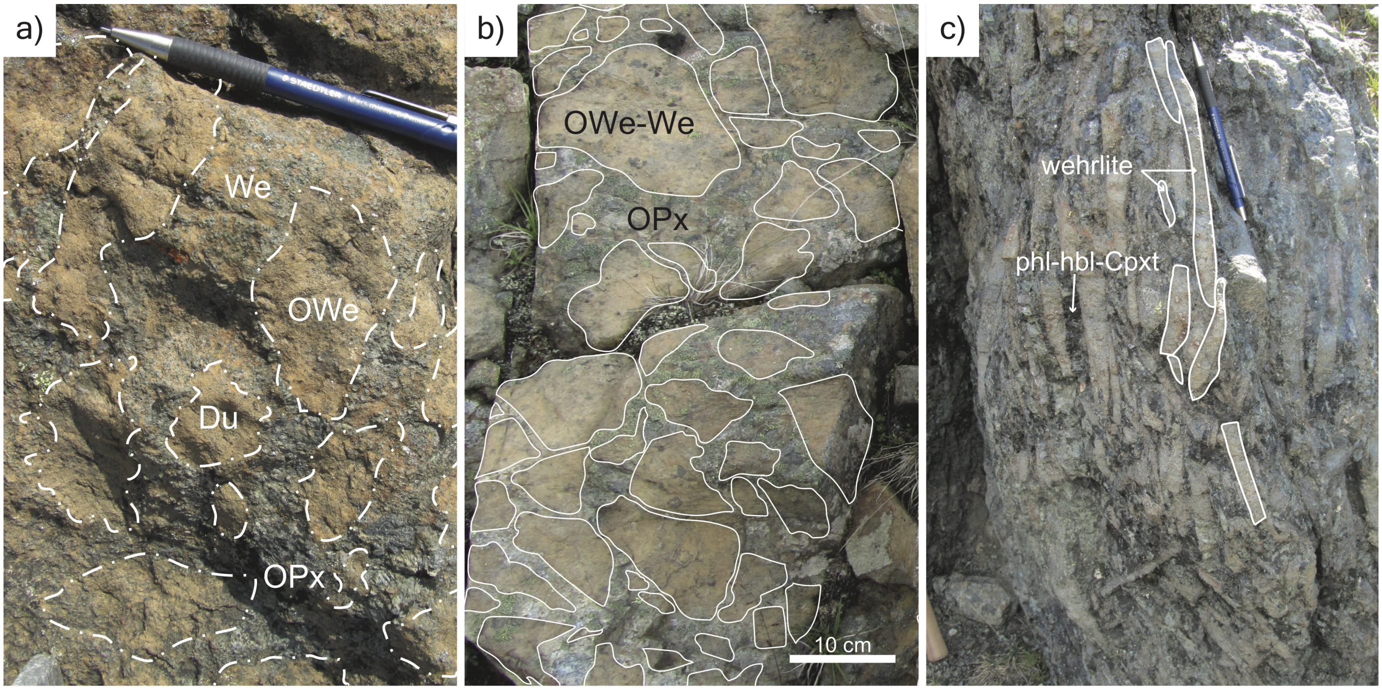

Fig. 12. Magmatic breccias in the Polaris intrusion. **a)** Subrounded fragments (<30 cm) of fine- to medium-grained (<1-3 mm) dunite (Du) and olivine wehrlite (OWe) with diffuse boundaries (dot-dash line) set in medium-grained (<3 mm) wehrlite (We) to olivine-clinopyroxenite (OPx) groundmass. **b)** Angular to rounded blocks of olivine wehrlite- wehrlite (OWe-We) with sharp to weakly gradational boundaries (solid line) set in a groundmass of medium-grained olivine clinopyroxenite (OPx). **c)** Angular to subangular tabular xenoliths of wehrlite in a coarse-grained phlogopite-hornblende-bearing clinopyroxenite groundmass (phl-hbl-Cpxt). See Fig. 10 for location.

4.1.7. Hornblende gabbro-diorite

Hornblende-bearing gabbro-diorite occurs predominately along the margins of the Polaris intrusion with the largest bodies in its western part. Hornblende gabbro-diorite sills also intrude metasedimentary rocks of the Lay Range assemblage in the metamorphic aureole of the intrusion (Nixon et al., 1997). Hornblende gabbro-diorite weathers dark grey and is typically lichen covered. Fresh surfaces are light grey to greenish-grey. Hornblende diorite is heterogeneous with variable grain size (<1-5 mm) and proportions of plagioclase and hornblende±clinopyroxene. Local foliated zones display shear fabrics (Fig. 13f) and hornblende mineral alignment (Fig. 14a). Hornblende-gabbro-diorite pegmatites typically contain 2-5 cm long hornblende crystals; some crystals are more than 15 cm long.

4.1.8. Felsic intrusions

Dm- to m-wide, fine- to medium-grained feldspathic dikes and plugs ranging from syenite to leuco-monzonite, crosscut hornblende clinopyroxenite, olivine clinopyroxenite, wehrlite, and dunite (Figs. 14a, b). Weathered surfaces of these intrusions are light blue-grey (Figs. 14b, c), whereas fresh surfaces are light greyish-white. Finely crystalline biotite is the principal mafic mineral and is only locally present. Feldspathic dikes are predominantly in the central part and, to a lesser extent, in the eastern parts of the intrusion (Fig. 3). Swarms of dikes trend northwest-southeast, roughly parallel to the regional tectonic grain. Less commonly, feldspathic dikes trend north-south. The contact zones of felsic intrusions locally enclose subangular to angular xenoliths of hornblendite, hornblende clinopyroxenite, and clinopyroxenite (Fig. 14c).

4.1.9. Magmatic Ni-Cu-PGE sulphides

Alaskan-type intrusions are generally known for their chromitite-Pt-Fe alloy mineralization hosted by dunite and derivative platiniferous placer deposits (e.g., Tulameen, Nixon et al., 1990). However, occurrences of magmatic Ni-Cu-PGE-sulphide mineralization in these intrusions are becoming increasingly documented (e.g., Turnagain, Scheel et al., 2005; Scheel, 2007; Jackson-Brown et al., 2015; Nixon et al., 2019a; Duke Island, Thakurta et al., 2014; Tulameen, Nixon et al., 2018; Nixon et al., 2019b). Polaris contains sparse Ni-Cu-PGE sulphide mineralization, mainly restricted to the northwestern and central parts of the intrusion. Sulphides are commonly hosted by reddish-brown weathering, malachite-stained, olivine-bearing clinopyroxenite, hornblende clinopyroxenite, and gabbro-diorite; a few sulphide occurrences are found in wehrlitic rocks (Fig. 3). The sulphides typically form fine disseminations in low modal abundances (<5 vol.%). Preliminary examination of mineralized rocks in thin section indicates that the most common sulphides are pyrrhotite, pentlandite, and chalcopyrite, locally accompanied by magnetite, with minor pyrite and bornite (Figs. 15a, b). The sulphides commonly form interstitial accumulations in the silicate framework and ovoid inclusions of crystallized sulphide melt in clinopyroxene or hornblende primocrysts (Figs. 15c, d). Whole rock analyses

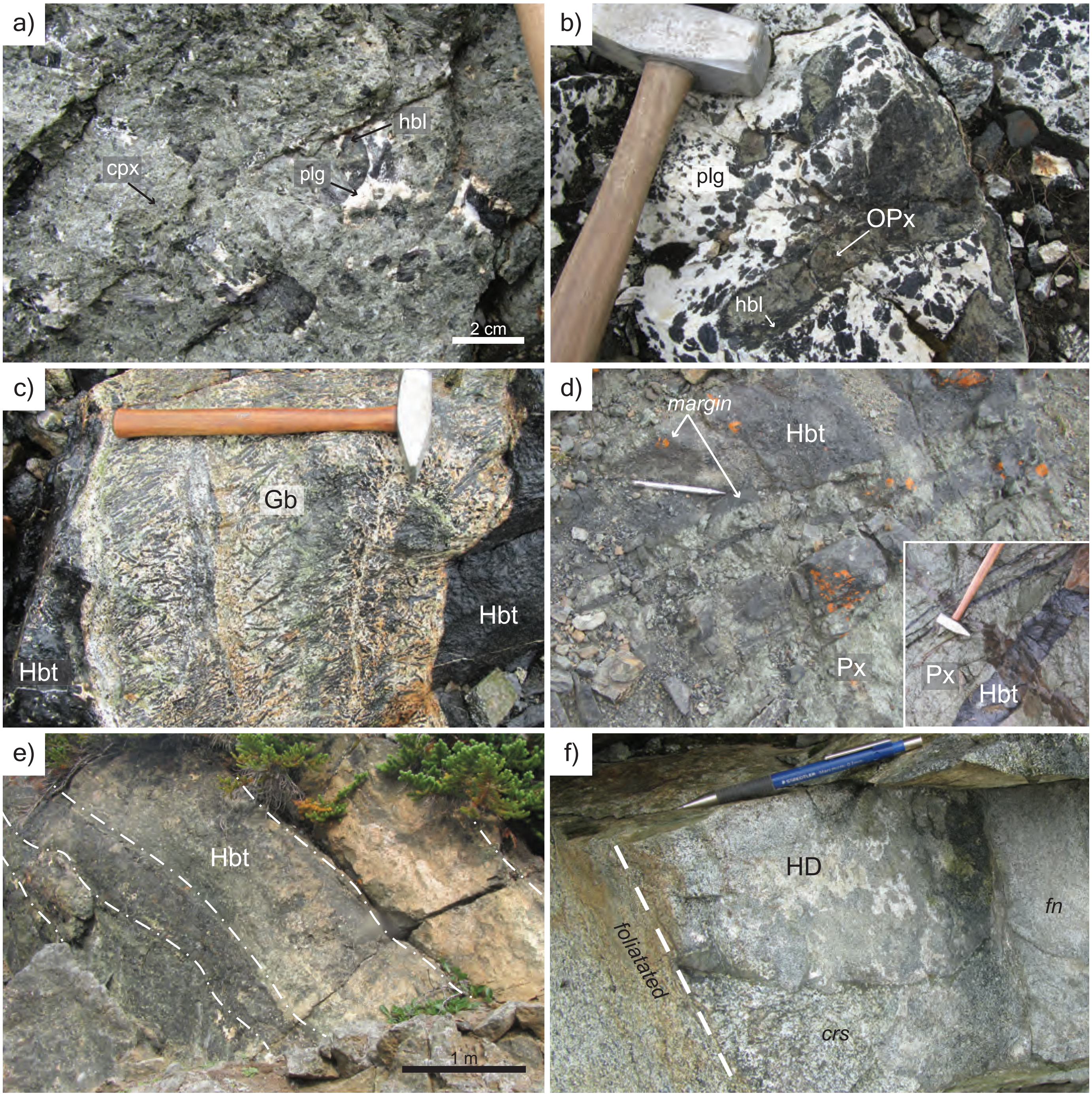

Fig. 13. Hornblende-bearing rocks in the Polaris intrusion. **a)** Feldspathic hornblende clinopyroxenite. Hornblende (hbl) forms euhedral-subhedral prismatic crystals (<2-4 cm long) intergrown with clinopyroxene and in plagioclase-rich segregations. **b)** Pegmatitic hornblende-bearing leucogabbro with highly saussuritized feldspar (plg) and enclaves of olivine clinopyroxenite (OPx) with hornblende-rich (hbl) rims. **c)** Hornblende gabbro dike (Gb) with internal dike-parallel layering. Prismatic hornblende crystals (up to 10 cm long) with long axes at high angles to the sharp external contact with massive pegmatitic hornblendite (Hbt) containing interstitial feldspar. **d)** Fine-grained magnetite-bearing hornblendite (Hbt) dikes with fine-grained margins intruding olivine-bearing clinopyroxenite (Px). Inset shows hornblendite dike and veins in sharp contact with olivine-bearing clinopyroxenite (Px). **e)** Magmatic layering in coarse-grained to pegmatitic (up to15 cm) hornblendite to gabbro (Hbt). **f)** Heterogeneous fine (fn)- to coarse (crs)-grained hornblende diorite (HD); locally foliated and with fabrics of possible kinematic significance.

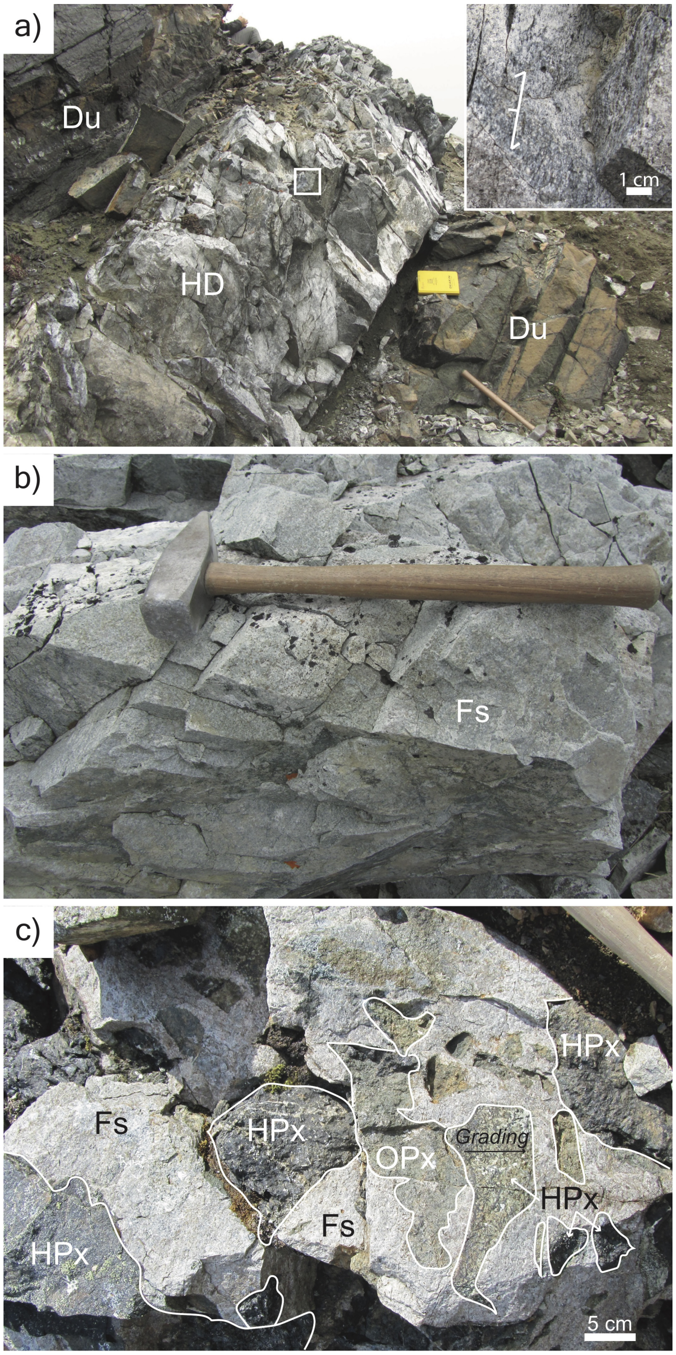

Fig. 14. Intrusive features of felsic to intermediate rocks in the central part of the Polaris intrusion. **a)** Fine- to medium-grained (<3 mm) hornblende-bearing diorite (HD) intruding dunite (Du). Inset shows dike with aligned elongate hornblende crystals. **b)** Medium-grained (<3 mm) hornblende-bearing syenite dike (Fs). **c)** Xenoliths of hornblende clinopyroxenite (HPx) and olivine clinopyroxenite (OPx) in syenite (Fs).

of mineralized hand samples have values up to 0.77 wt.% Cu, 1.3 g/t Pt and 1.8 g/t Pd (Mowat, 2015).

5. Contact aureole and country rocks

The metamorphic aureole of the Polaris intrusion is superimposed on metasedimentary and metavolcanic rocks of the Lay Range assemblage in the west and similar rocks of the Big Creek group in the east preserved beneath eastward-vergent thrust faults (Fig. 3). Hornfelsed rocks in the aureole typically have granoblastic textures, are variably foliated, and locally preserve compositional layering (Fig. 16a). The size of recrystallized grains (0.5 mm to 2 mm) generally increases within a few m of ultramafic-mafic rocks along the western intrusive contact and is accompanied by localized growth of granular (?)cordierite (<2 mm). Porphyroblastic, acicular to tabular amphibole (<5 mm) in the contact aureole has a weak to strong mineral alignment. Mapping beyond the northern termination of the Polaris intrusion identified strongly aligned amphibolite schist with a mineral lineation plunging 40-50° towards the west-southwest and cm-scale relict bedding oriented along the regional structural trend.

In the eastern metamorphic aureole, variably deformed, mylonitic gabbro-diorite intrudes Big Creek group strata in a structural sliver along the central-eastern thrust contact with ultramafic rocks (Figs. 4b, c). A mylonitic zone, typically less than 1 m wide, separates undeformed Polaris ultramafic rocks from the variably foliated gabbroic rocks. The gabbro-bearing thrust slice structurally overlies fissile black-grey phyllitic slates of the Big Creek group to the east (Fig. 3). Gabbroic textures range from fine- to coarse-grained and are cut locally by foliated and sheared basaltic dikes (Fig. 4b). The gabbros are in contact with west-dipping, foliated metasedimentary-metavolcanic strata containing small (≤1 mm) garnet porphyroblasts. Locally, these metasedimentary rocks display mesoscopic east-vergent folds (Fig. 16b).

The gabbroic intrusions in the eastern contact aureole were previously considered coeval with Polaris (Nixon et al., 1997). However, U-Pb age determinations in progress indicate that at least some of these gabbroic bodies may be significantly older (ca. 250 Ma) and genetically unrelated to the Polaris intrusive suite.

6. Discussion

6.1. Intrusion geometry

The Polaris intrusion is an elongate northwest- to southeast-trending intrusive body that locally exhibits weak magmatic layering and foliation in ultramafic, mafic, and hornblende-bearing units. This layering and foliation generally dips 30-50° to the west, broadly concordant with the host rocks. These observations are consistent with the interpretation that the Polaris intrusion is a sill-like body that intruded the Lay Range assemblage (Nixon et al., 1997). The internal distribution of rock types is asymmetric. Dunite, wehrlite, and clinopyroxenite predominate in the eastern and central parts of the intrusion, whereas mafic to feldspathic rocks, hornblende clinopyroxenites, gabbro-diorite, and syenite, occur mostly in the west.

6.2. Internal 'stratigraphy'

Along the eastern thrust margin of the Polaris intrusion, a narrow belt of ultramafic cumulates is locally preserved that

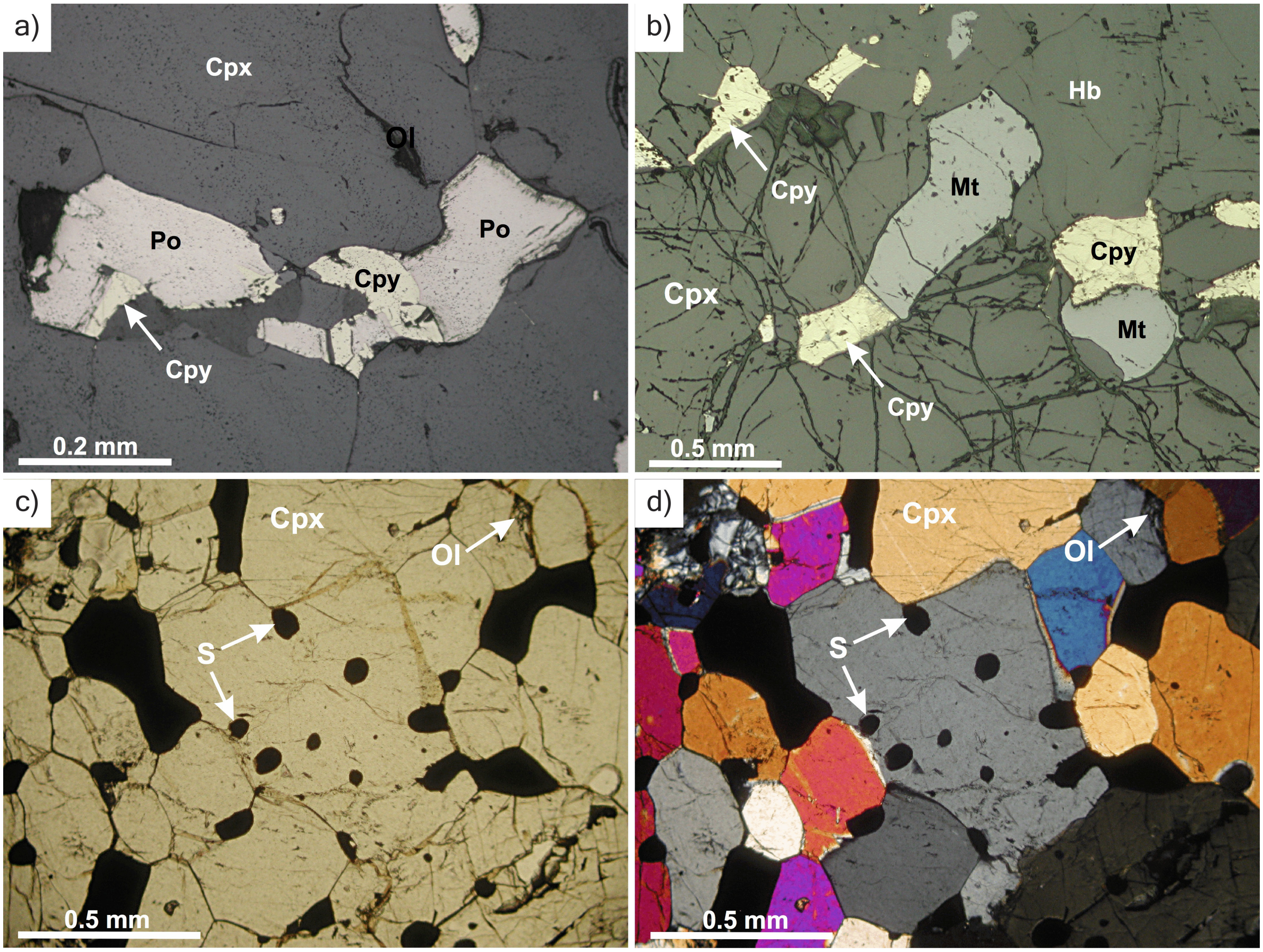

Fig. 15. Photomicrographs of sulphides in the Polaris intrusion. **a)** Finely disseminated chalcopyrite (Cpy) and pyrrhotite (Po) in olivine-bearing clinopyroxenite showing concentrations of sulphides at clinopyroxene (Cpx) grain boundaries. Sample 01GNX1-1-1A, reflected plane-polarized light. **b)** Disseminated chalcopyrite (Cpy) and magnetite (Mt) in hornblende (Hb)-bearing olivine clinopyroxenite. Sample 01GNX1-2-1A, reflected plane-polarized light. **c)** Disseminated magmatic sulphides in olivine (Ol)-bearing clinopyroxenite showing sulphide (S) melt inclusions in clinopyroxene (Cpx) and trapped melt at grain boundaries. Sample 01GNX1-1-1A, plane-polarized light. **d)** Same view as c), cross-polarized light.

passes gradationally (west to east) from dunite through olivine wehrlite and wehrlite to olivine clinopyroxenite at the eastern thrusted margin of the intrusion (Fig. 3). This zonation may have developed at the intrusive contact, which has been removed by faulting. However, the internal distribution of lithologies in the Polaris intrusion overall shows the reverse sense of zonation, from olivine-rich cumulates in the east to hornblende-bearing pyroxenite and gabbro-diorite in the west. This distribution of ultramafic-mafic rock types may represent internal stratigraphy that has been disrupted locally in zones of chaotic intermingling of cumulates.

The disruption of chromitite layers and schlieren in dunite and olivine wehrlite, the irregular and chaotic mixing of ultramafic rock types, localized mineral lineation of intrusive and country rocks, and evidence of repeated dike and sill emplacement indicate a combination of multiple intrusive events, remobilization of partially to fully crystallized cumulates of different competence, and reactive melt infiltration. Remobilization of the cumulate pile is evident from the disrupted and deformed chromitite. Magmatic disruption may have been produced through a variety of processes, including a combination of magmatic recharge, slumping, mechanical mixing of crystal-rich magma slurries, and possible syn-crystallization far-field tectonic stresses.

The chaotically intermingled units are interpreted to represent zones of episodic mingling between variably crystallized and/or consolidated cumulates of differing rheology (e.g., Fig. 10e). Relationships indicating ductile behavior, such as shearing and disaggregation of dunite and wehrlite by intrusion of olivine clinopyroxenite in chaotically intermingled unit rocks, conflict with observations for dunite intrusion into clinopyroxene-rich rocks. These relationships suggest multiple events of mixing

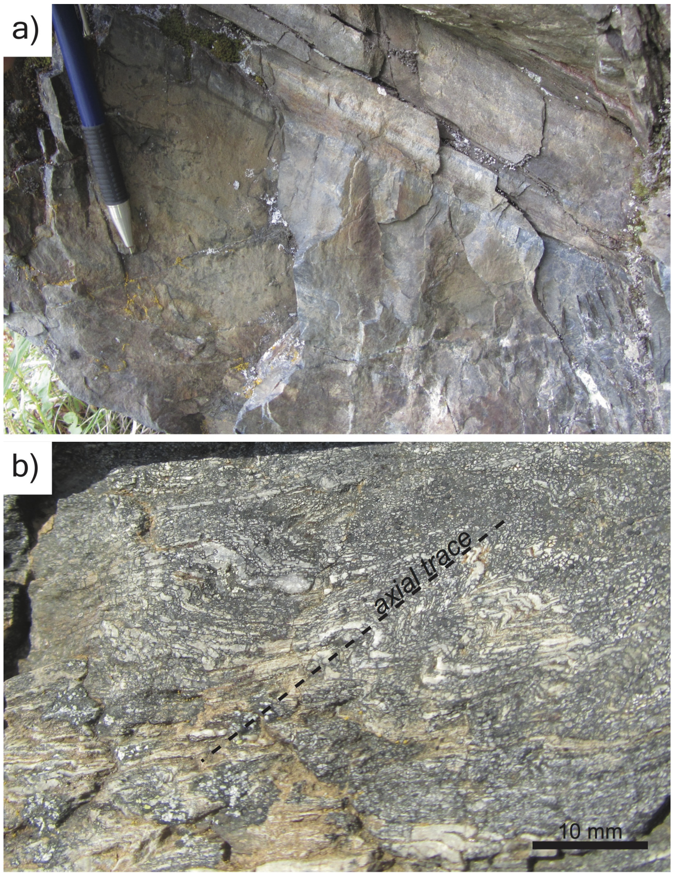

Fig. 16. Hornfelsed metasedimentary rocks in the metamorphic aureole of the Polaris intrusion. **a)** Cm-scale bedding in fine-grained metasedimentary rocks of the Lay Range assemblage, northwestern part of contact aureole. **b)** Foliated, fine-grained siliciclastic rocks of the Big Creek group showing small, open, eastward-vergent folds; hinge line trend and plunge: 308°-14°.

and mingling, involving cumulates at different points in their thermal histories and rheological states. Local dense swarms of (olivine) clinopyroxenite dikes, with cm-scale offshoots, that crosscut dunite and olivine wehrlite suggest that injection of evolved clinopyroxene-saturated magma was locally important. Possible reactive replacement of dunitic/olivine wehrlitic cumulates by these evolved magmas is indicated by the common cm- to m-scale irregular, patchy, clinopyroxene-rich pods and dikes that have gradational contacts, which may be diffuse, with the surrounding olivine-rich rocks (Figs. 10b, c). Olivine clinopyroxenite and clinopyroxenite comprise the matrix in magmatic breccias, and net-veined, 'honeycomb'-textured rocks, which contain angular to sub-rounded blocks and plates of dunite, olivine wehrlite, and wehrlite (Fig. 12), are consistent with brittle fragmentation of a coherent host. Crosscutting olivine clinopyroxenite dikes with sharp boundaries also indicate late-stage intrusive episodes. Finally, brittle faulting is prevalent throughout the intrusion and accentuated in olivine-rich lithologies as noted by intense and complete serpentinization of the shear planes.

6.3. Inferences from the country rocks

Incorporation and possible assimilation of country rocks by magma(s) parental to the Polaris intrusion is evident from the map-scale xenolithic bodies of hornfelsed country rock within intrusion boundaries. Assimilated country rock is a potential source of sulphur (e.g., Lesher, 2017) and may be a potent reductant (Tomkins et al., 2012), which may have contributed to sulphide saturation in the magma, leading to segregation and crystallization of immiscible sulphide melt. Structures in country rocks along the eastern flank of the intrusion are consistent with previous interpretations (Monger, 1973; Ferri et al., 1993; Nixon et al., 1997) that the Polaris complex was thrust eastward atop the North American continental margin.

7. Conclusion

Detailed mapping has helped to refine lithological units in the Polaris intrusion as defined by Nixon et al. (1997) as well as their contact relationships. The geometry, zonation, and local magmatic layering of the intrusion indicate that it is likely a sill. Variable textures in chromitites and the presence of chaotically intermingled units with evidence for mingling of different melts and cumulates, and characteristics indicative of melt infiltration, suggest a disrupted magma chamber, characterized by periods of episodic magma input and reservoir recharge.

Although the Ni-Cu-PGE potential of Alaskan-type ultramafic-mafic intrusions in British Columbia and Alaska is increasingly recognized (Scheel et al., 2005; Scheel, 2007; Scheel et al., 2009; Thakurta et al., 2014; Jackson-Brown et al., 2015; Jackson-Brown, 2017; Nixon et al., 2018), the fundamentals of how Alaskan-type intrusions form is poorly understood (e.g., Thakurta, 2017). To help better understand these bodies, U-Pb geochronologic, petrographic, and trace element studies of the Polaris intrusion are ongoing.

Acknowledgments

Thank you to the Abraham family of the Takla First Nation for their support and assistance in field accommodation. The senior author thanks the Hogem batholith project team for their support in the field. Thanks to SilverKing helicopters for exemplary service and to Abigail Fraser for expediting field preparations and support throughout the field season. Salary support to the senior author is gratefully acknowledged through an NSERC CGS-M scholarship. Funding for this project is provided by the Geological Survey of Canada's Targeted Geoscience Initiative 5 Program, the British Columbia Geological Survey, and a NSERC Discovery Grant to James Scoates. Constructive criticisms of the manuscript by Alex Zagorevski, and Fil Ferri are greatly appreciated.

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