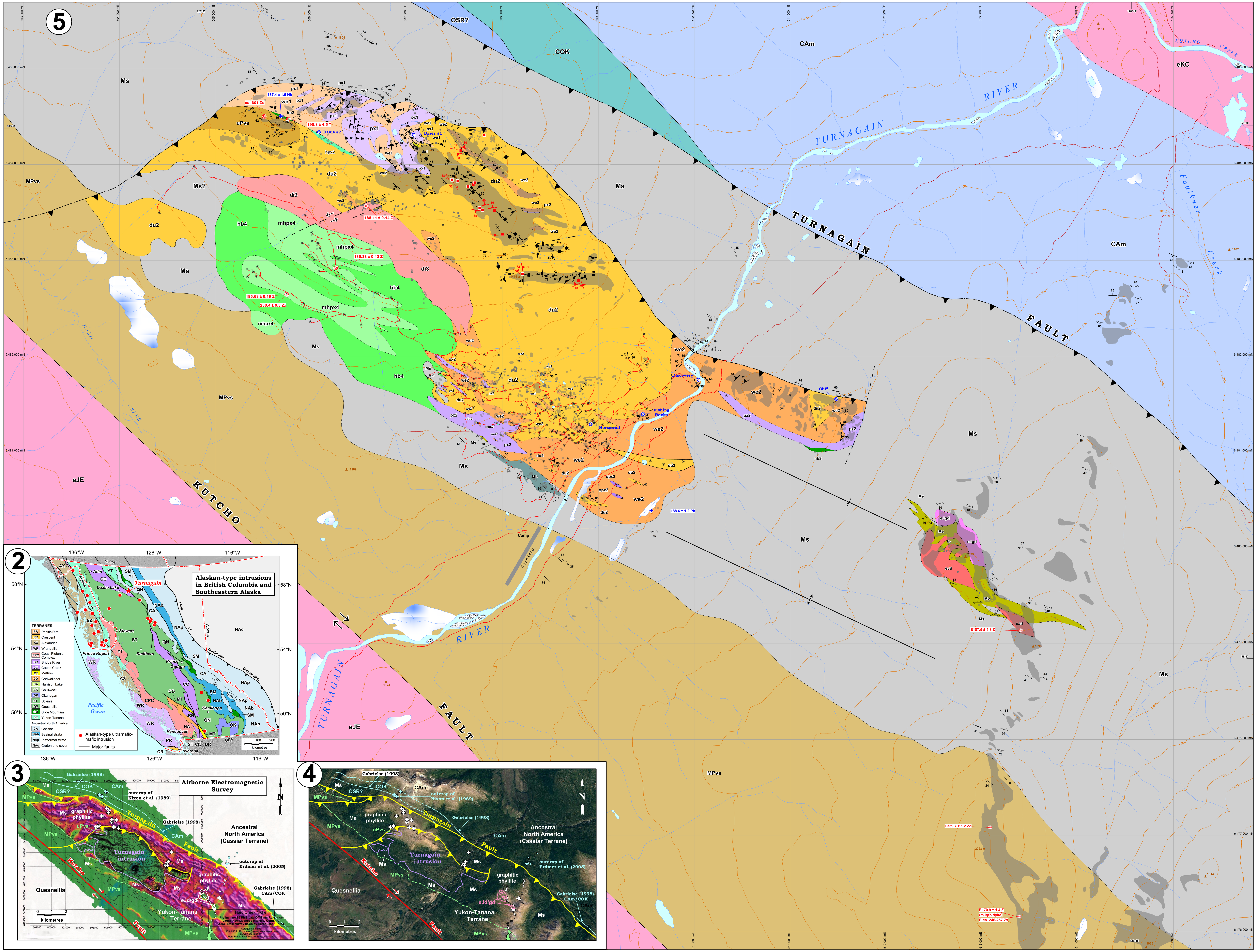


BC Geological Survey

GEOSCIENCE MAP 2017-1

Geology and Geochronology of the Turnagain Ultramafic-Mafic Intrusion, British Columbia

parts of NTS 104I/07 and 10

Sheet 1 of 2

G. T. Nixon*, J. E. Scheel**, R. M. Friedman**, C. J. Wall**, J. Gabites**, D. Miller* and J. S. Scoates**

* British Columbia Geological Survey ** University of British Columbia

0 0.5 1 kilometres

Scale 1:10 000

MAP LEGEND

QUESNEL TERRANE

EARLY JURASSIC

- **eJE** Eaglehead Pluton: biotite-hornblende quartz monzonite, granodiorite and quartz diorite

YUKON-TANANA TERRANE

EARLY JURASSIC

TURNAGAIN ULTRAMAFIC-MAFIC INTRUSION

Intrusive Phase 4

- **hb4** Black to dark greenish grey, coarse-grained hornblendite, clinopyroxene hornblendite and minor clinopyroxenite; locally magnetite/biotite-bearing and pegmatitic; rarely feldspathic; cut by leuco-diorite dykes
- **mhpx4** Dark greenish grey, medium- to coarse-grained, magnetite-hornblende clinopyroxenite and magnetite clinopyroxenite; locally pegmatitic and biotite-rich; cut by leuco-diorite dykes

Intrusive Phase 3

- **di3** Dark grey-green to pale grey, medium- to coarse-grained hornblende diorite to melanocratic diorite; minor feldspathic hornblendite, quartz diorite, granodiorite and tonalite

Intrusive Phase 2

- **hb2** Black to dark greenish grey, coarse-grained hornblendite; locally pegmatitic
- **hpx2** Dark greenish grey, medium- to coarse-grained, hornblende clinopyroxenite and minor clinopyroxenite; locally pegmatitic
- **px2** Dark grey-green, medium-grained to pegmatitic clinopyroxenite
- **opx2** Grey to grey-green, medium-grained to pegmatitic olivine clinopyroxenite
- **we2** Dark greenish grey, variably serpentinized, medium- to coarse-grained wehrlite; locally contains minor dunite and olivine clinopyroxenite; commonly cut by clinopyroxenite dykes
- **du2** Dark grey to greenish grey, variably serpentinized, medium-grained dunite; locally contains minor remobilized chromitite layers and schlieren; minor wehrlite and olivine clinopyroxenite; commonly cut by wehrlite and clinopyroxenite dykes

Intrusive Phase 1

- **px1** Grey to grey-green, medium-grained to pegmatitic olivine clinopyroxenite
- **we1** Dark greenish grey, variably serpentinized, medium- to coarse-grained wehrlite; locally contains minor dunite and olivine clinopyroxenite; commonly cut by clinopyroxenite dykes
- **du1** Dark grey to greenish grey, weakly serpentinized, medium-grained dunite

EARLY JURASSIC

- **eJgd** Medium to pale grey granodiorite
- **eJd** Medium grey diorite

CARBONIFEROUS
Upper Pennsylvanian

- **uPvs** Dark grey-green volcanic wacke and phyllite

Mississippian to Pennsylvanian (and possibly younger)

- **MPvs** Mafic to felsic volcanic/volcaniclastic and interbedded sedimentary rocks including tuffaceous phyllite, argillite, chert, quartz-sericite schist and marble

Mississippian

- **Mb** Dark grey-green basaltic sill
- **Mv** Interbedded dark grey-green tuff, tuffaceous phyllite; minor wacke, limestone and rare graphitic phyllite; in part equivalent to Klinkit Group
- **Ms** Black, dark grey to grey-green, graphitic and pyritic phyllite and slate with minor thin interbedded limestone and wacke; in part equivalent to Swift River Group

ANCESTRAL NORTH AMERICA (CASSIAR TERRANE)

EARLY CRETACEOUS

- **eKC** Cassiar Batholith: biotite-hornblende granite, granodiorite and quartz monzonite

ORDOVICIAN TO SILURIAN

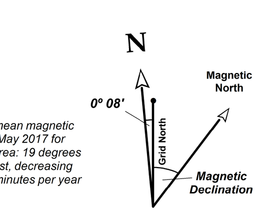
- **OSR?** Road River Formation(?): siltstone and black pyritic and calcareous shale, slate and phyllite

CAMBRIAN TO LOWER ORDOVICIAN

- **COK** Kechika Formation: argillaceous limestone and calcareous shale

LOWER CAMBRIAN

- **CAm** Atan Group: micaceous quartzite, mica schist, siltstone and minor marble



Approximate mean magnetic declination May 2017 for centre of map area: 19 degrees 31 minutes east, decreasing annually 17.7 minutes per year

MAP SYMBOLS

- Geological contact, defined or approximate
- Geological contact, inferred
- Geological contact, inferred from geophysical data
- Steeply dipping fault, defined or approximate
- Steeply dipping fault, inferred
- Reverse fault, defined or approximate (teeth on upper plate)
- Reverse fault, inferred from geophysical data (teeth on upper plate)
- Strike-slip fault, steeply dipping, approximate (right-lateral)
- Strike-slip fault, steeply dipping, approximate (left-lateral)
- Chromitite locality
- Historical sulphide showing
- Outcrop examined
- Outcrop too small to show at map scale
- Drillhole collar
- Drillhole orientation (shown in cross-section)

Structure

- Antiform, upright to overturned (projected from Erdmer et al., 2005)
- Synform, upright to overturned (projected from Erdmer et al., 2005)
- 70 Bedding, tops unknown, inclined
- 64 Cumulate layering, tops unknown, inclined, vertical
- 75 Chromitite layering, tops unknown, inclined, vertical
- 35 Minor fold of chromitite layers showing axial-plane dip
- 64 Dyke (typically wehrlite or clinopyroxenite), inclined, vertical
- 70 Early cleavage or schistosity (S1), inclined, vertical
- 55 Crenulation cleavage (S2), inclined
- 70 Foliation induced by shearing, inclined, vertical
- 17 Crenulation lineation showing plunge
- 63 Minor fold of S1 foliation (F2) showing axial-plane dip
- 17 Minor fold of S1 folation (F2) showing plunge

Geochronology

- 185.33 ± 0.19 Z — U-Pb date (Ma, 2 sigma); Z, zircon; d, detrital; x, xenocrystic; T, titanite; determined by R. M. Friedman; E, U-Pb date of Erdmer et al. (2005); mJqfp, Middle Jurassic quartz-feldspar porphyry dyke
- 188.2 ± 1.6 Ph — $^{40}Ar/^{39}Ar$ date (Ma; 2 sigma); Hb, hornblende; Ph, phlogopite; determined by J. Gabites

Topography

- Lake
- Flooded land (swamp)
- Stream or river
- Contour (100m)
- 1290 Spot height (m)
- Road (dirt)
- Gravel bar

Base Map Information

Base map produced from digital Terrain Resource Inventory Management (TRIM) topographic database (1:20,000 scale), British Columbia Ministry of Forests, Lands and Natural Resource Operations.

Universal Transverse Mercator Projection (Zone 9), North American Datum 1983 (NAD83). Elevation in metres above mean sea level. Contour interval is 100m.

Data Sources

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Contributions

Contributions to the geology of the Turnagain intrusion were made by A.C. Hitchins, C. Baldys, B.K. Northcote, J.W. Kyba, D. Héon and G.P. Ross (Hard Creek Nickel Corporation).

Recommended Citation

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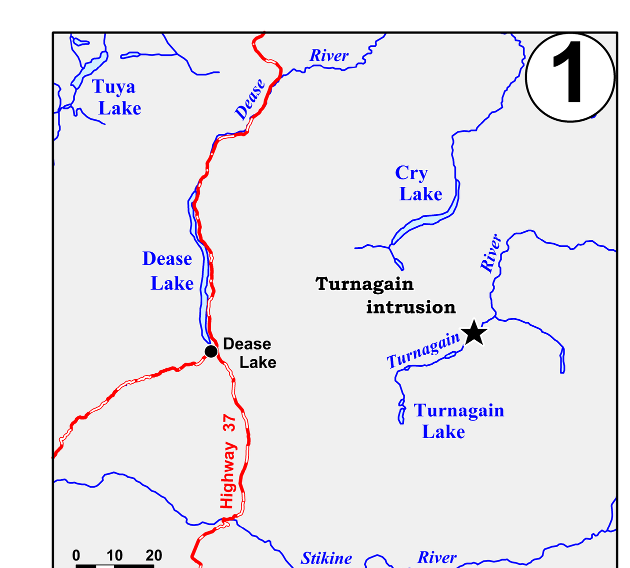

BC Geological Survey

GEOSCIENCE MAP 2017-1

Geology and Geochronology of the Turnagain Ultramafic-Mafic Intrusion, British Columbia

parts of NTS 104I/07 and 10

Sheet 2 of 2

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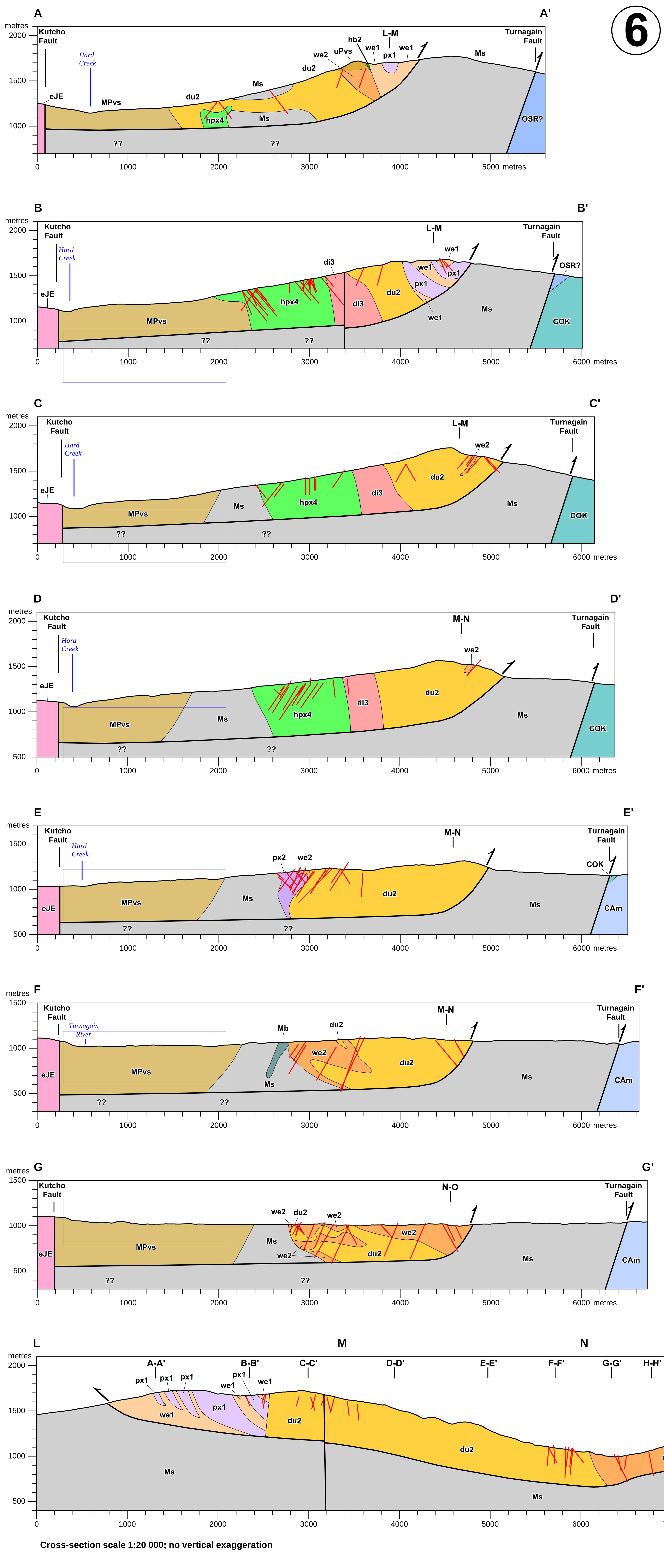
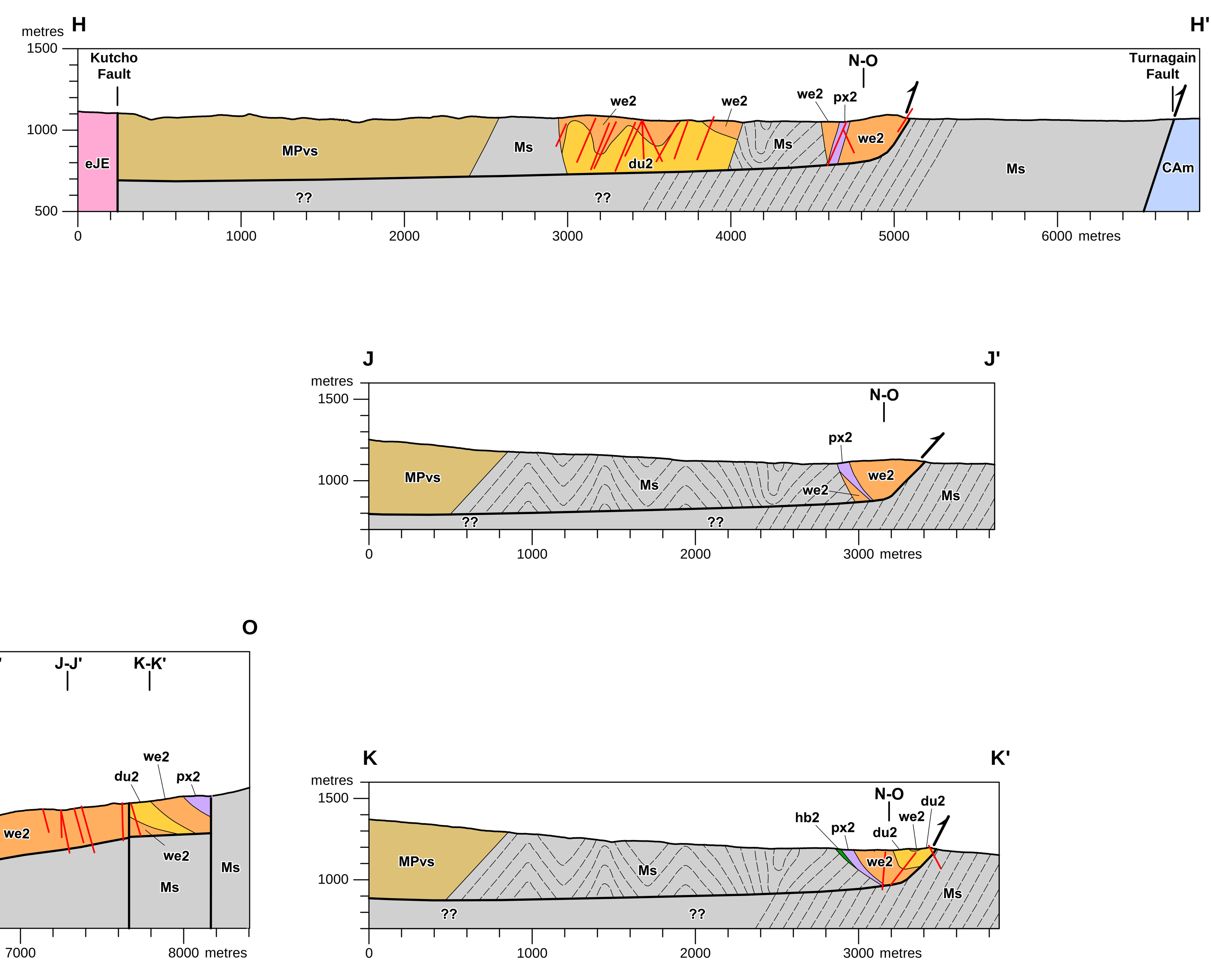
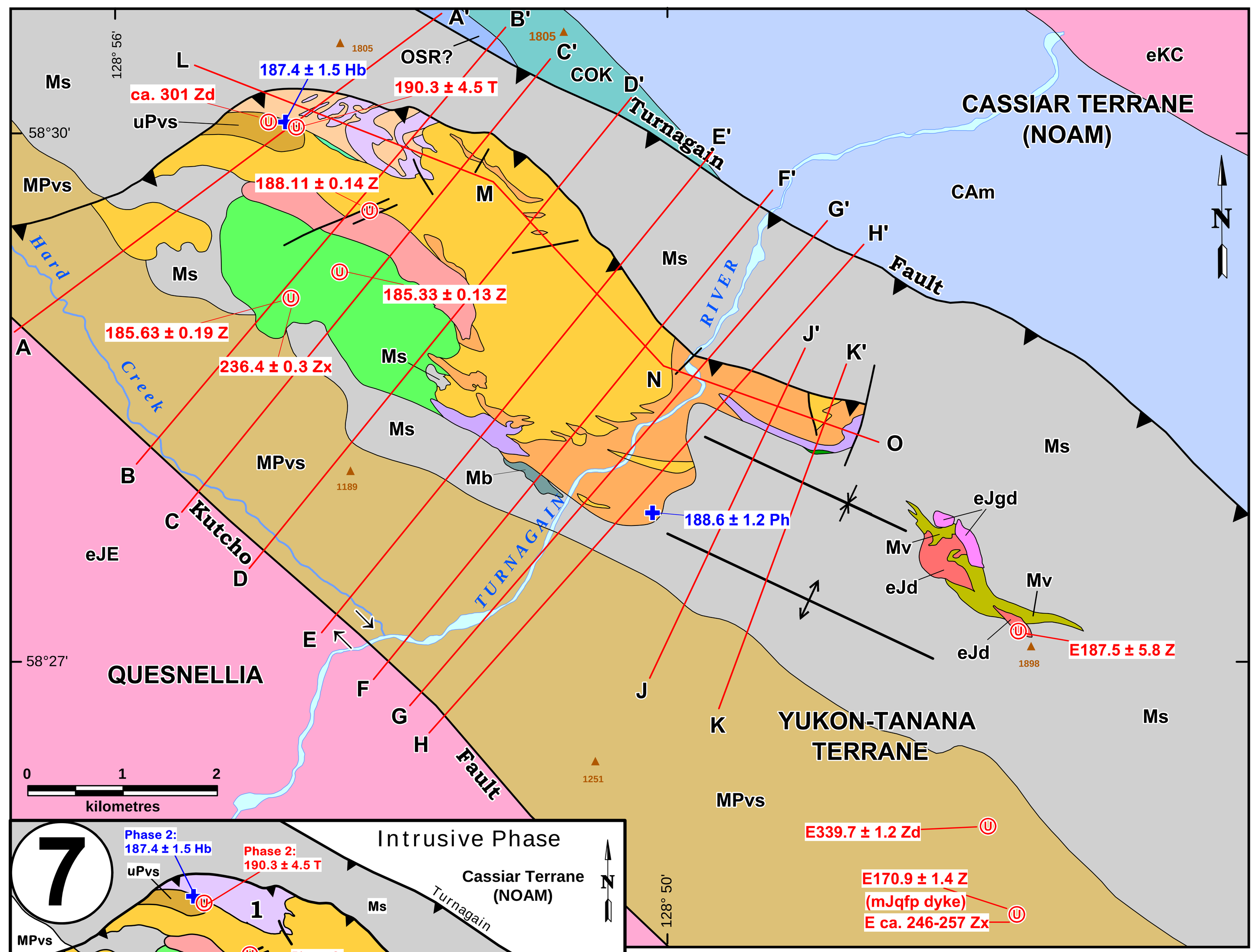
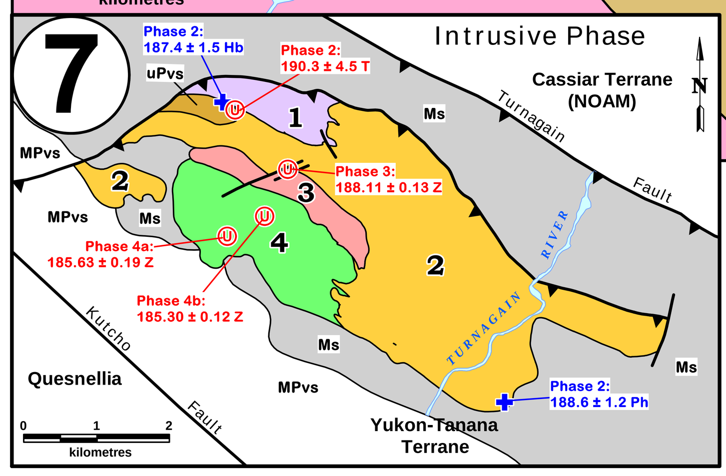
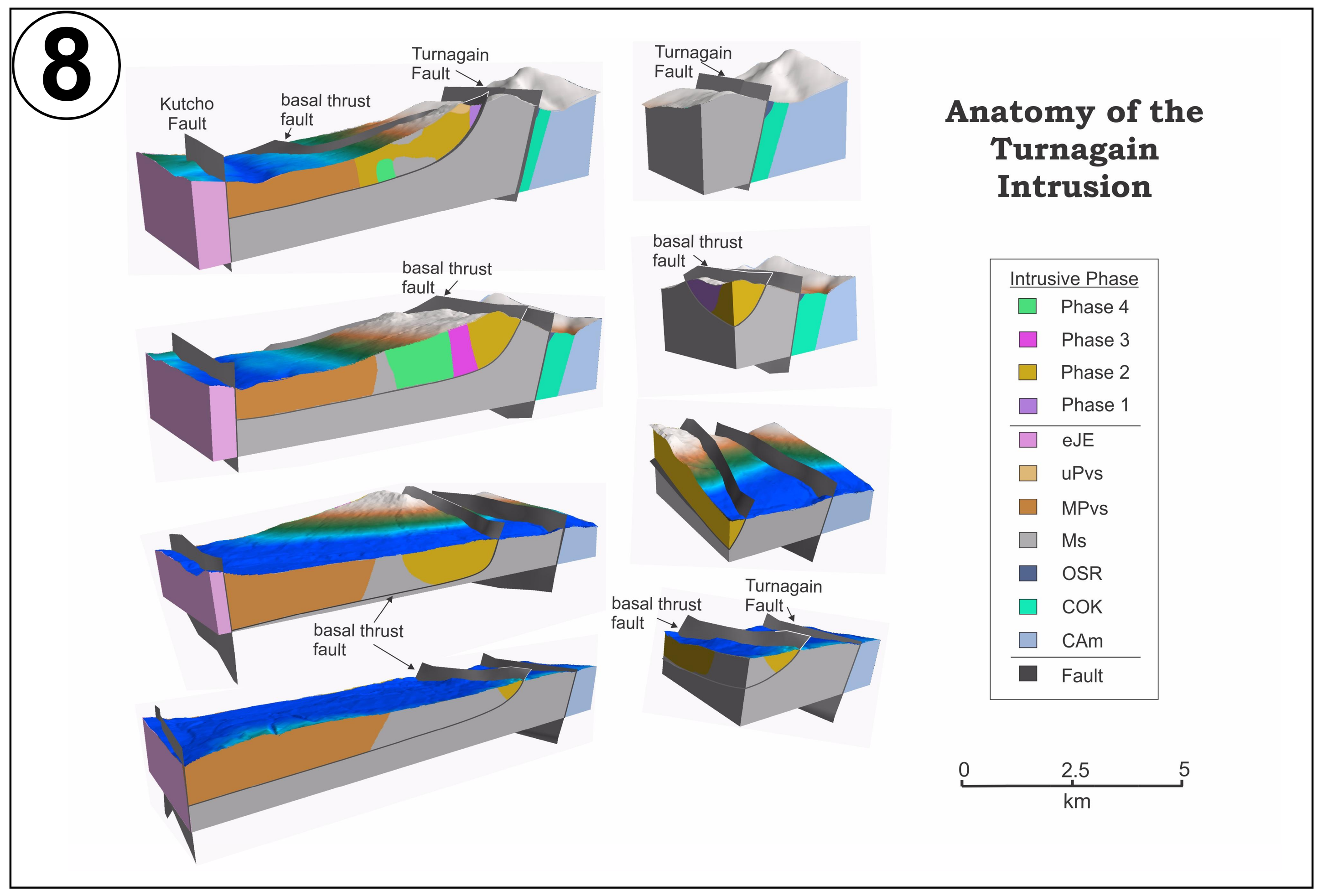
** British Columbia Geological Survey* *** University of British Columbia*











Turnagain Ultramafic-Mafic Intrusion

Introduction

The Early Jurassic Turnagain Alaskan-type intrusion (25 km^2) is located 70 km east of Dease Lake in northern British Columbia (Fig. 1). The ultramafic-mafic body lies within the accreted arc terranes of Quesnellia/Yukon-Tanana, east of the Early Cretaceous, post-accretionary Kutcho fault and west of displaced miogeoclinal strata of Ancestral North America (Cassiar terrane, Fig. 2; Colpron and Nelson, 2011; Gabrielse, 1985). The Turnagain intrusion belongs to a global class of ultramafic-mafic intrusions emplaced in supra-subduction zone environments that are gaining prominence as an exploration target for magmatic Ni-Cu-platinum group element (PGE) mineralization (Nixon et al., 2015; Manor et al., 2016). The Turnagain body is unusually enriched in Ni(-Co-Cu-PGE) sulphides compared to typical Alaskan-type intrusions. Low-grade Ni-sulphide mineralization at Turnagain ranks ninth among the world's largest deposits in terms of contained Ni metal, constituting a total resource of 1842 Mt @ 0.21 wt % Ni and 0.013 wt % Co (Mudd and Jowitt, 2014).

The main Ni mineralization is hosted chiefly by wehrlite and clinopyroxenite, and the principal sulphide minerals are pyrrhotite, pentlandite and chalcopyrite. Platinum group minerals documented in the youngest part of the intrusion include platinum- and palladium-bearing arsenides, antimonides and tellurides (Jackson-Brown et al., 2014). The origin of the mineralization is directly related to contamination of primitive arc magmas by crustal material. Critical contributions of sulphur and graphite from carbonaceous phyllite in the wallrocks led to the reduction of oxidized parental arc magmas and triggered sulphide saturation (Scheel, 2007).

The Turnagain intrusion has been regarded as a typical Alaskan-type body zoned from a dunite-wehrlite core to a clinopyroxenite-hornblende clinopyroxenite-hornblendite margin (Clark, 1980). The compositional and textural features of Alaskan-type intrusions are commonly related to crystal accumulation from fractionating mafic-ultramafic magmas residing deep in the crust. The origin of the zoning has been explained by re-intrusion of hot, incompletely solidified crystal cumulates to higher crustal levels promoted by diapiric uprise and/or regional deformation (e.g., Findlay, 1969; Irvine, 1974; Clark, 1980). More recent studies draw attention to emplacement of zoned ultramafic suites in narrow conduit systems, rooted in the mantle, which serve as efficient traps for upgraded metal-laden magmas (e.g., Manor et al., 2016). In the latter case, lithological zoning appears related to accretion of cumulates on conduit walls coupled with multiple injection of variably fractionated magmas (Manor et al., 2016 and references therein).

Regional setting

Prior to this study, greenschist-facies graphitic strata that host the Turnagain intrusion were interpreted to form part of the displaced North America cratonic margin and to conformably overlie Cambro-Ordovician stratigraphy of the miogeocline (Gabrielse, 1998; Erdmer et al., 2005). The latter authors also documented a conformable relationship between the graphitic strata and overlying Mississippian metasedimentary-metavolcanic rocks and showed that the succession is deformed by kilometre-scale, upright to northeastward-verging folds. They concluded that the entire succession represents a volcanic arc or back-arc assemblage built on the edge of Ancestral North America.

A regional airborne electromagnetic (EM) survey conducted during mineral exploration in the area indicates that graphitic strata hosting the Turnagain intrusion show a marked EM response (conductivity; warm colours in Fig. 3) not shared by ultramafic or surrounding metavolcanic and metasedimentary rocks (Figs. 3-4). Our mapping traverses north and east of the Turnagain intrusion demonstrate that the sharp EM boundary separates highly conductive graphitic rocks from poorly conductive strata of the miogeocline (Atan Group and Kechika Formation; Nixon et al., 1989). This EM boundary truncates the stratigraphic units mapped by Gabrielse (1998) and passes through a 800m gap in outcrop presumed to be occupied by the Kechika Formation (Erdmer et al., 2005; Figs. 3-4). We infer that this boundary represents a terrane-bounding fault (herein named the Turnagain fault; Figs. 3-4) that delineates the Early Jurassic thrust emplacement of late Paleozoic to early Mesozoic arc assemblages (Quesnellia/Yukon-Tanana terranes) onto the Ancestral North American craton. The graphitic phyllite and overlying metavolcanic-metasedimentary strata appear correlative in part with the Swift River and Klinkit Groups of southern Yukon-Tanana terrane (Roots et al., 2006).

Geology of the Turnagain Intrusion

A compilation of the geology of the Turnagain intrusion incorporates historical and modern exploration work, as well as geology documented east of the intrusion (Erdmer et al., 2005; J. E. Scheel, unpublished data; Fig. 5). A series of simplified geological cross-sections (A-A` to K-K`) and a longitudinal section (L-M-N-O, Fig. 6) showing drill core control depict contact relationships with the country rocks and intrusive components of the complex (Fig. 7). The surface geology, cross-sections and drill core information were used to construct the conceptual 3D architecture of the intrusion (Fig. 8).

The Turnagain ultramafic-mafic intrusion forms an elongate body (8 x 3 km) oriented within the regional structural trend (Figs. 3-4). The northern and eastern margins of the intrusion are marked by a southwesterly dipping thrust fault that has emplaced ultramafic rocks onto graphitic strata of Mississippian age in the footwall. Intrusive contacts with hornfelsed wallrocks are largely preserved along the southern and western margins of the intrusion (Figs. 5-8).

Geological mapping has established four distinct intrusive phases (Fig. 7; from oldest to youngest): ***Phase 1***, interlayered wehrlite and clinopyroxenite with minor dunite; ***Phase 2***, mainly dunite and wehrlite with minor clinopyroxenite and localized occurrences of clinopyroxenite and hornblendite near the margins; ***Phase 3***, melanocratic to mesocratic diorite and lesser feldspathic hornblendite; and ***Phase 4*** hornblende clinopyroxenite, magnetite clinopyroxenite and hornblendite cut by minor leuco-diorite dykes. Contacts between intrusive phases are typically sharp and locally marked by intrusive breccias.

Phase 1 forms a small body at the northern edge of the complex. Here, interlayered (tens of metres to centimetre-scale) wehrlite and clinopyroxenite with minor dunite form a steeply dipping trough or synform plunging steeply to the southeast. The original attitude of this structure may have been modified by motion along the adjacent thrust fault.

Phase 2 dunite-wehrlite(-clinopyroxenite-hornblendite) occupy the core of the Turnagain intrusion and intrude Phase 1 rocks. This intrusive phase is the most voluminous and hosts the main Ni-sulphide mineralization. The dunite and wehrlite units are generally massive although mappable units of wehrlite locally occur in dunite and *vice versa*.

Phase 3 diorite forms an elongate body separating Phase 2 from Phase 4 rocks in the central part of the complex. Centimetre- to metre-scale layering of mesocratic and melanocratic diorite is well preserved in some outcrops. Intrusive breccias with dunite clasts derived from Phase 2 set in a dioritic groundmass are observed locally.

Phase 4 hornblende clinopyroxenite, magnetite-clinopyroxenite and hornblendite form a poorly exposed body at the northwestern margin of the complex. These rocks are cut locally by thin leuco-diorite dykes. Examination of drill core and sparse outcrops reveals sparse centimetre-scale layering locally involving thin horizons of magnetitite and Fe-Cu sulphides. These Cu-PGE-enriched sulphides are a current exploration target and potentially form an additional economic resource.

Geochronology

Emplacement of the various Intrusive phases of the Turnagain Alaskan-type complex were investigated by U-Pb and $^{40}Ar/^{39}Ar$ geochronology (Figs. 5-7). U-Pb dating of accessory minerals (zircon, titanite) by chemical abrasion-isotope dilution-thermal ionization mass spectrometry (CA-ID-TIMS) yields the following $^{206}Pb/^{238}U$ dates (±2σ) that are interpreted as crystallization ages: Phase 2 hornblendite, 190.3±4.5 Ma (titanite); Phase 3 mela-diorite, 188.11±0.14 Ma (zircon); and Phase 4 clinopyroxenite (4a) and a leuco-diorite dyke (4b), 185.63±0.19 and 185.33±0.13 Ma (both zircon), respectively. $^{40}Ar/^{39}Ar$ dating of Phase 2 wehrlite and hornblendite yields plateau dates of 188.6±1.2 Ma (2σ, phlogopite) and 187.4±1.5 Ma (hornblende), respectively, that represent cooling ages (nominally 500°C and 300°C for the closure temperatures of hornblende and biotite, respectively). The latter dates represent minimum ages for the emplacement of Phase 2 ultramafic cumulates.

U-Pb dating of detrital zircons has established the age of the country rocks. Multigrain fractions of air-abraded detrital zircons from a volcanic wacke in an enclave of metavolcanic-metasedimentary lithologies at the northern margin of the Turnagain intrusion yield a large range of $^{206}Pb/^{238}U$ dates (ca. 244 to 1652 Ma), reflecting Pb loss and Proterozoic inheritance (Scheel, 2007; Figs. 5-6). One concordant fraction yields a $^{206}Pb/^{238}U$ date of 301.4±1.2 (2σ) Ma (uppermost Pennsylvanian close to the Carboniferous-Permian boundary) which is interpreted to be the maximum depositional age of this volcanic wacke. Erdmer et al. (2005) reported a weighted mean $^{206}Pb/^{238}U$ date of 339.7±1.2 (2σ) Ma (Middle Mississippian) for multigrain fractions of air-abraded zircon from a felsic schist in the lower part of the metavolcanic unit (Figs. 5-6). Thus, the strata which host the Turnagain intrusion are Carboniferous in age (Middle Mississippian to Upper Pennsylvanian and possibly younger, as discussed below).

Southeast of the Turnagain intrusion, a granodiorite body cutting the graphitic phyllite-metavolcanic contact has yielded multigrain air-abraded $^{206}Pb/^{238}U$ zircon dates ranging from 183.9 to 192.4 Ma with an interpreted crystallization age of 187.5±5.8 (2σ) Ma (Erdmer et al., 2005; Figs. 5-6). One discordant zircon fraction in this sample shows Proterozoic inheritance (1105±440 Ma). To the south, a granitic dyke cutting metavolcanic stratigraphy and the main regional foliation yields a wide dispersion of concordant to nearly concordant $^{206}Pb/^{238}U$ dates (170.3–256.5 Ma) representing multigrain air-abraded zircon fractions (Figs. 5-6). Erdmer et al. (2005) favoured the weighted mean date of the youngest zircon fractions (170.9±1.4 (2σ) Ma) as the crystallization age of this rock and considered the older dates to reflect Permian inheritance (ca. 257 Ma). Anomalous dates are also given by chemically abraded zircon xenocrysts recovered from a Phase 4 clinopyroxenite in the Turnagain intrusion. These xenocrysts yield a concordant early Late Triassic age ca. 236 Ma (Figs. 5-6). The Permian and Triassic zircons may be sourced by intrusion(s) at depth or possibly reflect Permo-Triassic stratigraphy involved in unrecognized structural complexity.

Conclusions

The field observations and geochronological results for ultramafic-mafic rocks of the Turnagain Alaskan-type intrusion place robust constraints on the internal architecture and temporal evolution of the complex, the timing of mineralization, and regional tectonic events.

Emplacement of the Turnagain intrusion occurred in discrete stages over a period of at least 3 million years (ca. 188-185 Ma). The geochronology results agree with the sequence of intrusive events recorded by geological relationships observed in the field. The span of intrusive activity must be regarded as a minimum since intrusive Phase 2 yields $^{40}Ar/^{39}Ar$ cooling dates as old as 188 Ma; and the oldest Phase 1 component of the Turnagain complex remains to be dated.

Mineralization in the Turnagain intrusion is hosted by two separate sub-intrusions. The main Ni resource is contained in the Phase 2 intrusion dated at 188-190 Ma, whereas the Cu-PGE-enriched sulphides in Phase 4 clinopyroxenites and hornblendites were emplaced several million years later (ca. 185-186 Ma). The dating results indicate the presence of two distinctive sulphide saturation episodes in the Turnagain intrusion that took place in independent mineral systems: an early event that produced substantial Ni-sulphide mineralization in the older Phase 2 cumulates; and a later event that gave rise to Cu-PGE mineralization in the younger Phase 4 rocks.

The crude zonal arrangement of internal lithologies appears somewhat serendipitous in that it is primarily governed by the episodic intrusion and deposition of discrete batches of cumulates derived from parental magma(s) at various stages of evolution. However, the localized occurrence of thin marginal units of hornblendite and clinopyroxenite within the volumetrically dominant Phase 2 dunites and wehrlites must reflect second-order post-emplacement processes. Therefore, realistic models for the origin of zoned ultramafic-mafic complexes such as Alaskan-type intrusions are likely to be complex, and successful models for their evolution will require calibration by further detailed geochronological studies.

Regional folding and thrusting in the Turnagain area occurred in response to deformation accompanying the accretion of Quesnellia/Yukon-Tanana terranes to the miogeocline. Regional deformation postdates emplacement of the youngest Phase 4 intrusive component of the Turnagain intrusion. The granitic dyke dated by Erdmer et al. (2005) places a minimum age on the major phase of deformation (ca. 171 Ma). Thus, the accretion of Quesnellia to the North American continent is constrained to be younger than ca. 185 Ma (Early Jurassic - Pliensbachian) and older than ca. 171 Ma (early Middle Jurassic – Aalenian).

Acknowledgments

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