Structural and stratigraphic control of porphyry and related mineralization in the Treaty Glacier – KSM – Brucejack – Stewart trend of western Stikinia

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Recommended citation: Nelson, J., and Kyba, J., 2014. Structural and stratigraphic control of porphyry and related mineralization in the Treaty Glacier – KSM – Brucejack – Stewart trend of western Stikinia. In: Geological Fieldwork 2013, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2014-1, pp. 111-140.

Abstract
One of the most important mineral trends of northwestern British Columbia extends from near the town of Stewart north to the Treaty Glacier, in the western part of the Stikine arc terrane. Major deposits along this trend include Kerr-Sulphurets-Mitchell (KSM), Brucejack, Silbak-Premier, Big Missouri, Scottie Gold and Red Mountain. All are hosted by volcanic and sedimentary rocks of the Hazelton Group (Lower Jurassic) and its subvolcanic feeders (193-195 Ma Premier porphyries near Stewart; Mitchell intrusions at KSM). Although the Hazelton Group is widespread throughout Stikinia, the narrow, consistently NNW-SSE trend of mineralization along a 60 km strike length suggests structure-controlled magmatic and hydrothermal systems, possibly influenced by basement anisotropies. The Jack Formation, a unique basal Hazelton unit restricted to the flanks of the McTagg anticlinorium, is characterized by quartz-rich arkoses and polymictic pebble conglomerates with high-level intrusive, felsic volcanic and quartz clasts. Stratigraphic and sedimentologic data from Jack Formation sections are consistent with depositional control by penecontemporaneous, basin-bounding faults and by volcanic centres. The McTagg anticlinorium was probably a topographic high during sedimentation. Initial sedimentation at the Treaty Glacier and Brucejack sections on the eastern side of the anticlinorium is marked by sharpstone conglomerates derived from immediately underlying Stuhini Group (Triassic) and may represent mechanical weathering fronts on a gently sloping upland, whereas at the Bruce Glacier section to the west, basal units include isolated remnants of carbonaceous mudstone that are overlain by thick (100 m +) sections of polymictic cobble-boulder conglomerate, which imply abrupt basin deepening and underfilled conditions followed by uplifting, significant relief, and a proximal but integrated drainage system. An overlying predominantly fine-grained siliciclastic section thins eastward from ~ 400 m at the Bruce Glacier section to ≤ 80 m at the Treaty Glacier section. Local cross beds in mass flow sandstones at the Bruce Glacier section indicate derivation from the east, away from the area now occupied by the McTagg anticlinorium. Sandstone megaclast-bearing olistostromes in equivalent carbonaceous mudstones at the Brucejack section attest to fault-induced uplift and cannibalization of previously deposited Jack Formation sandstones. Andesitic pyroclastic and epiclastic volcaniclastic rocks in the middle of the Jack Formation represent an episode of intense volcanism. Black mudstone intraclasts in the volcaniclastic units indicate that background deep-water sedimentation resumed during intervals of volcanic quiescence. Thick coarse volcaniclastic sections at the Bruce Glacier and Treaty glacier sections suggest proximity to discrete coeval volcanic centres. In the Iron Cap section, highly altered lower Jack Formation arkosic sandstones and polymictic pebble conglomerates occur as screens within the potassic and phyllic-altered porphyry body, which is overlain by a thin andesitic volcaniclastic blanket and unaltered Jack conglomerates, showing the coeval relationship of sedimentation, intrusion, alteration and local volcanism. At the Bruce Glacier section, the volcaniclastic facies grades back into a mudstone-rich sedimentary section and a return to deep- water sedimentation. In marked contrast, at the Treaty Glacier section to the east, rocks above the volcaniclastic facies indicate shallow-marine sedimentation (basal limestone beds with shelly fauna, sandstones with interference ripples and plant debris, polymodal paleocurrents). Apparently, as with the onset of Jack Formation sedimentation, the region on the eastern side of the McTagg anticlinorium was high standing relative to the eastern side. Integration of facies variations in the Jack Formation with first-order Cretaceous structures leads to a model in which the eastern margin of the McTagg anticlinorium was once a basin-bounding master growth fault. Accordingly, the KSM porphyries and their associated alteration haloes were channeled along this fault, and the Brucejack epithermal system to the east developed adjacent to a complex set of related north-trending and east-trending faults. The Early Jurassic structural regime may have been transtensional or purely extensional.

Keywords: Stewart, Treaty Glacier, Iskut region, KSM, Brucejack, Hazelton Group, Jack Formation, Early Jurassic, McTagg anticlinorium

1. Introduction

Although it has long been appreciated that basement structures extending west from ancestral North America influenced depositional and structural patterns in Cordilleran platformal cover rocks (Fig. 1; e.g., Aitken and Long, 1978; Cecile et al., 1997; McMechan, 2012) and focused mineralization at deposits such as Sullivan and Pine Point (Höy et al., 2002; Nelson et al., 2002), the possibility that basement to accreted arc terranes exerted a similar control has not been fully investigated. Most of British Columbia's copper and gold endowment is in latest Triassic to Early Jurassic porphyry and related deposits of the Quesnel and Stikine arcs (Fig. 1). In Quesnellia, these deposits and their igneous hosts form arc-parallel, eastward-younging belts (Logan and Mihalynuk, 2013, in press). In contrast, those

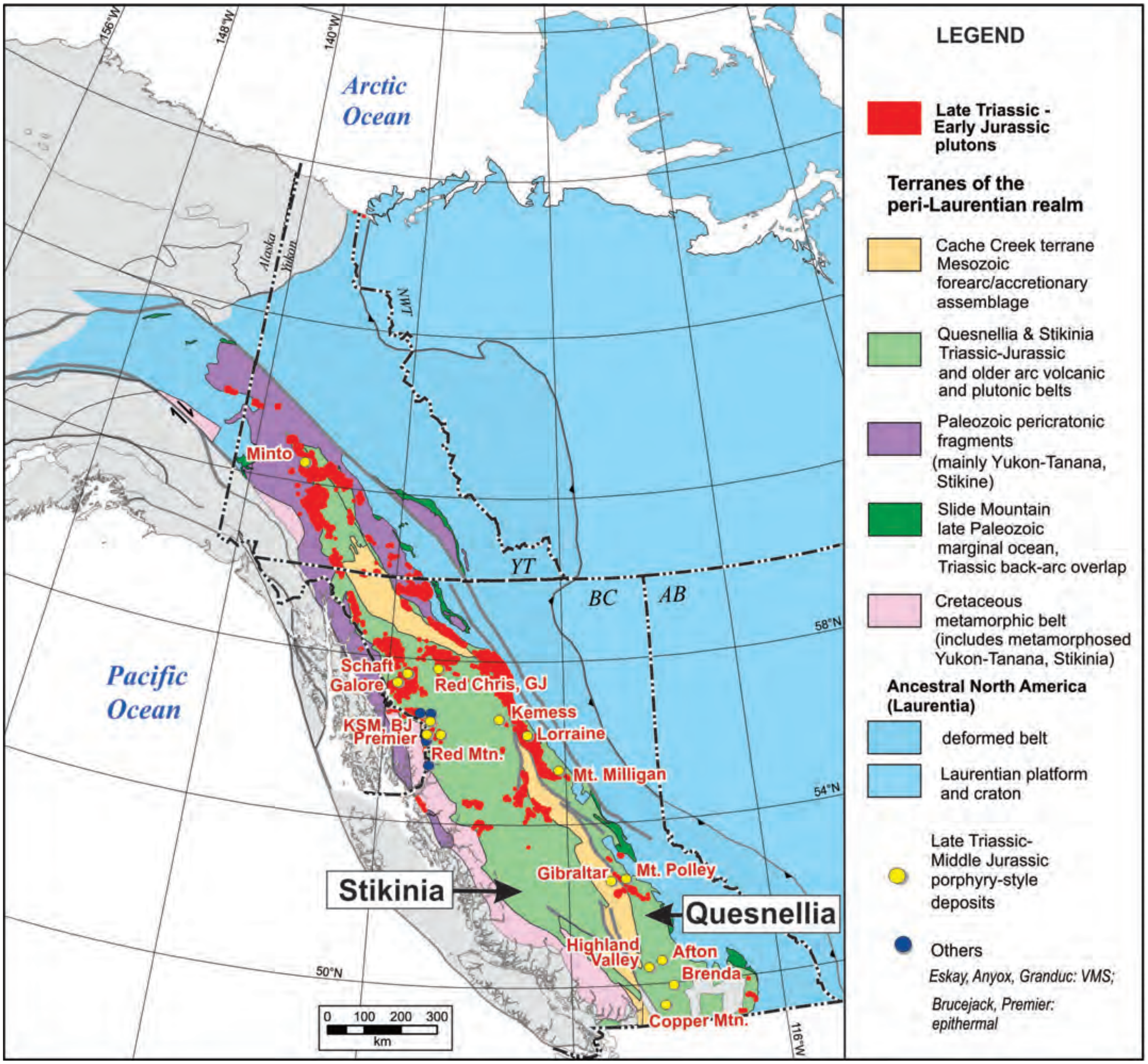


Fig. 1. Tectonic setting of Triassic-Jurassic porphyry and related deposits of Quesnellia and Stikinia in the northern Cordillera of BC and Yukon, from Nelson et al. (2013).

in Stikinia form several discrete clusters and trends of differing ages, including Kemess, Iskut (Red Chris, GJ), Schaft Creek-Galore Creek, and Treaty Glacier-KSM-Brucejack-Stewart (Fig. 1).

The Treaty Glacier-KSM-Brucejack-Stewart trend is one of the most productive and promising in northwestern British Columbia (Figs. 2, 3). Major deposits include Kerr-Sulphurets-Mitchell (KSM), Brucejack, Silbak-Premier, Big Missouri, Scottie Gold, and Red Mountain. All are hosted by, and related to, volcanosedimentary rocks of the Hazelton Group (Lower Jurassic) and its subvolcanic feeders, the ~ 195 Ma Texas Creek and Premier porphyries near Stewart (Alldrick, 1993) and Mitchell intrusions at KSM (Kirkham and Margolis, 1995). Mineralized bodies define a northerly trend, extending discontinuously for ~ 60 km, from near the town of Stewart north to Treaty Glacier (Figs. 2, 3). Although the Hazelton Group is widespread throughout Stikinia, the narrow, consistently NNW-SSE trend of mineralization along a 60 km strike length suggests structure-controlled magmatic and hydrothermal systems. Furthermore, Alldrick (1993) considered that local pre-ore structures controlled mineralization at Silbak Premier, Big Missouri and Scottie Gold, and work by Pretivm Resources (2013) at Brucejack suggests that replacements and stockworks in basal Hazelton Group strata formed adjacent to north-striking

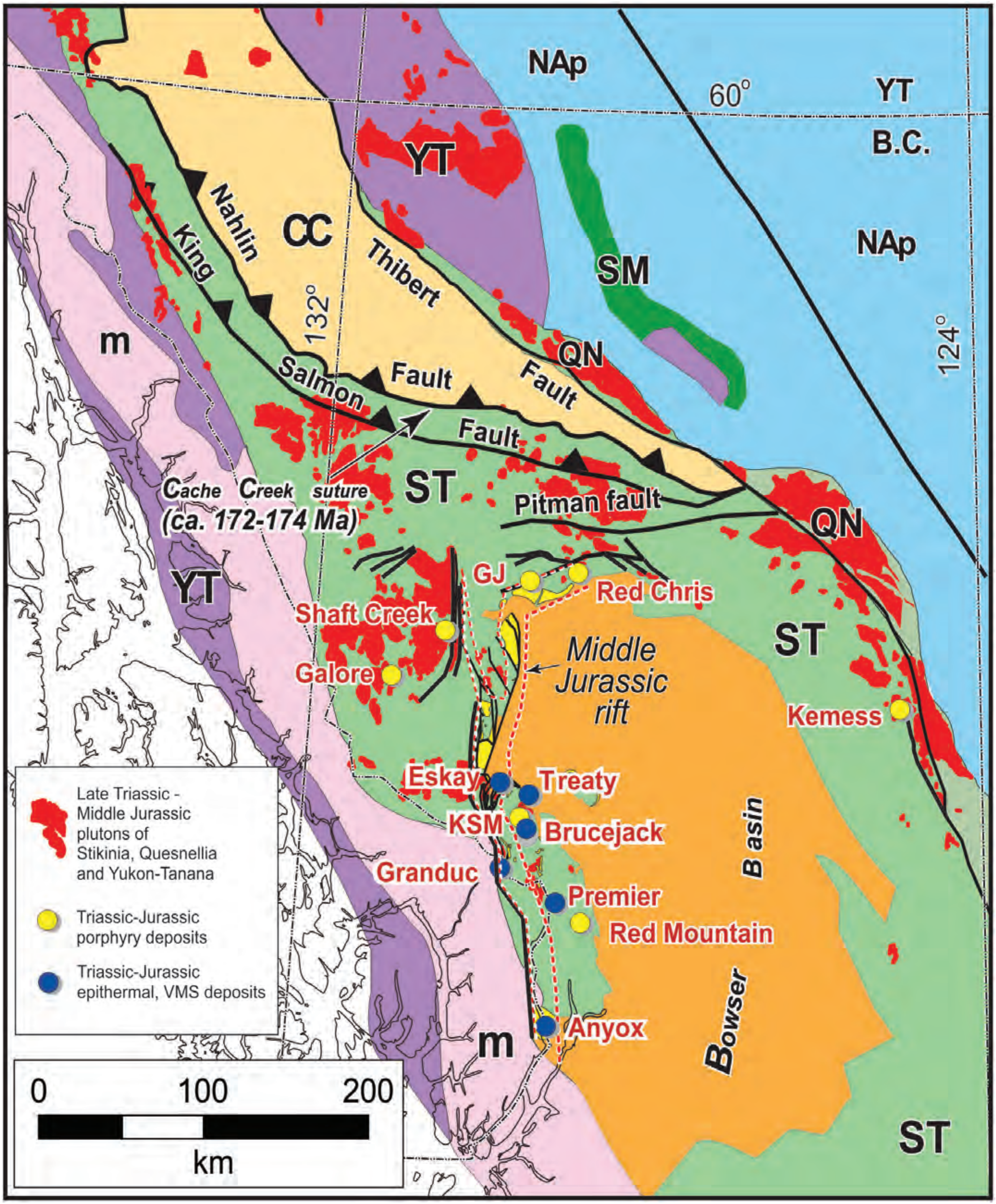


Fig. 2. Tectonic and structural setting of Triassic-Jurassic porphyry and related deposits in northern Stikinia, from Nelson et al. (2013). Terrane abbreviations: CC = Cache Creek, Na = North America (platformal), QN = Quesnellia, SM = Slide Mountain, ST = Stikinia, YT = Yukon-Tanana; m = metamorphic rocks of the Coast Plutonic complex.

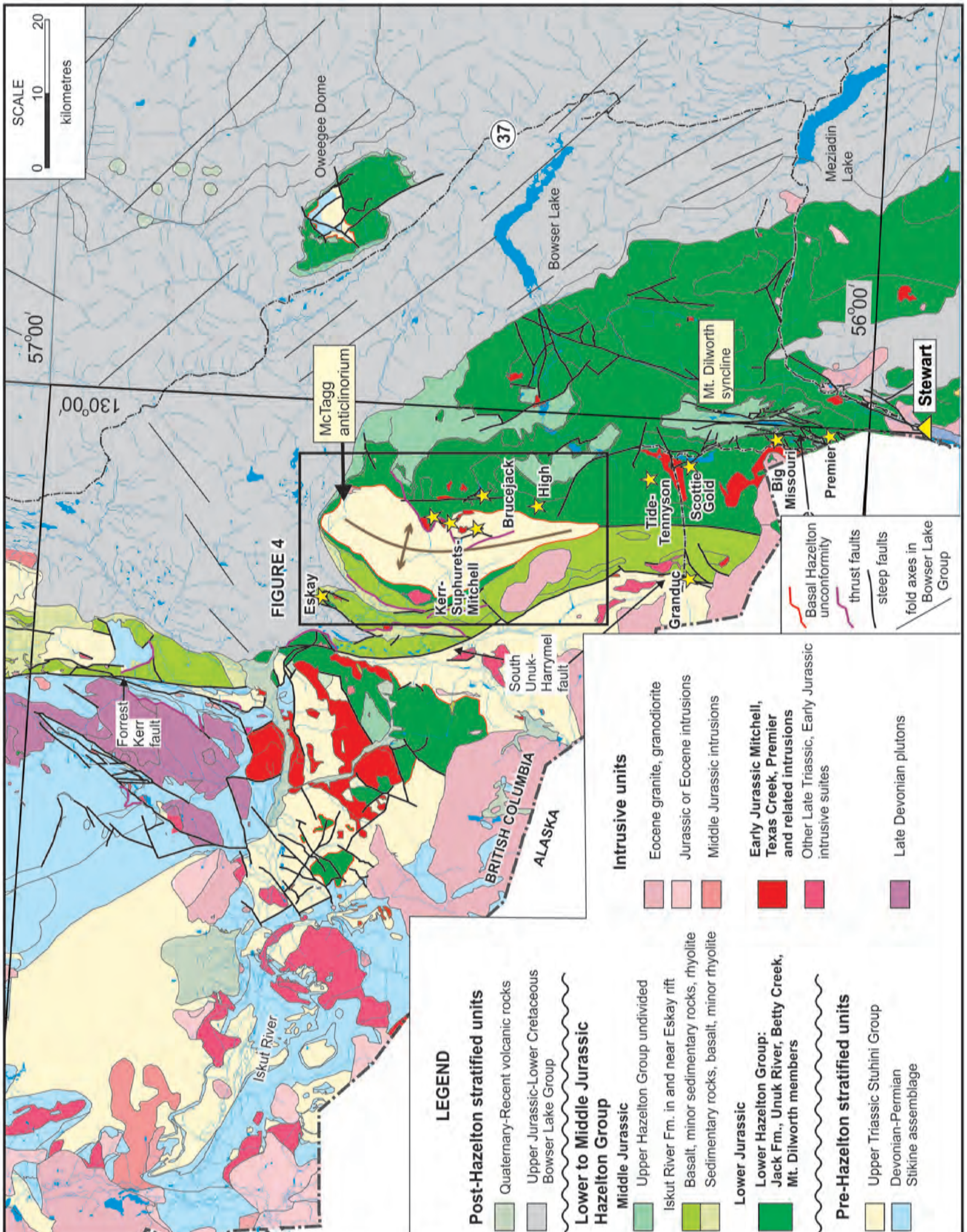


Fig. 3. Treaty-Stewart trend and western Iskut region geology and mineral deposits, generalized from the digital geological map of British Columbia 2005 from Massey et al. (2005).

growth faults. Moreover, the northerly and northeasterly structures along the trend, which formed during the Cretaceous as part of the Skeena fold and thrust belt, are highly discordant to the overall northwesterly Skeena grain, hinting at a local control by basement anisotropies.

Fault reactivation creates a structural veil that typically obscures previous events. To fully document reactivation of basement structures and penecontemporaneous faulting, integrated stratigraphic, sedimentologic, structural, geochronologic, and geophysical data are required (e.g., Holdsworth et al., 1997). Herein we present stratigraphic and sedimentologic data from basal Hazelton strata (Jack Formation), the favoured host for porphyry and epithermal deposits, exposed near the McTagg anticlinorium (Fig. 3). Together with a first-order analysis of Cretaceous structural patterns, these data provide circumstantial evidence consistent with structural control of sedimentation, magmatism, and mineralization along the Treaty Glacier-KSM-Brucejack-Stewart trend.

2. Mineralization in the Treaty Glacier-KSM-Brucejack-Stewart trend

Mineralization along the trend is diverse, even within individual deposits, indicating complex, episodic ore formation. Besides porphyries, there are gold stockworks, shear-hosted veins, hydrothermal breccias and replacements (Alldrick, 1993). Past gold producers include Silbak-Premier (1918-1968 and 1989-1997), Big Missouri (1927-1942), and Scottie Gold (1981-1984). Owing to major exploration programs in the last five years, the Kerr-Sulphurets-Mitchell (KSM) Cu-Au porphyries and high-grade gold zones at Brucejack are approaching the mine development stage. Seabridge Gold submitted its EA application for the KSM deposit in April 2013. Proven and probable reserves for the KSM porphyries are over 2.16 billion tonnes grading 0.21% Cu, 0.55 g/t Au, 2.74 g/t Ag and 44.7 ppm Mo (December 2012, pre-feasibility study). In 2013, 23,800 m of drilling on the Deep Kerr target identified a Cu-Au-rich zone with a weighted average of drill intercepts grading 0.46 g/t Au and 0.71% Cu over a width of 220 metres (Seabridge release, 23-11-13, not 43-101 compliant). At the adjoining Brucejack property, the Valley of the Kings (VOK zone) hosts a probable reserve totalling 15.1 Mt grading 13.6 g/t Au and 11 g/t Ag (June 2013 feasibility, Pretivm Resources, 2013). A 10,000 tonne underground bulk sample has been excavated and is currently being processed to further validate the deposit. Preliminary results indicate that over 4200 ounces of gold had been recovered from 8090 tonnes, with recovery from the remaining 1810 tonnes pending (Pretivm Resources, 2013). Other exploration projects in the area in 2013 (Figs. 3, 4) include the Tide-Tennyson porphyry-epithermal target south of the Frank Mackie Glacier by HDI Brigade; the High property between Brucejack and the Frank Mackie Glacier by Teuton Resources, and Premier-Big Missouri by Ascot Resources.

3. Regional setting: Stikine terrane

Stikinia is a long-lived arc terrane in the Intermontane belt of the Canadian Cordillera. At its northern end near Tulsequah and its far western extent in the Coast Mountains, it developed near the Yukon-Tanana terrane, which is partly underlain by siliciclastic basement units rifted from the edge of ancestral North America (Fig. 1; Nelson et al., 2006). The oldest rocks in Stikinia are Devonian to Mississippian arc-related volcanic and plutonic bodies and accompanying sedimentary strata of the Stikine assemblage (upper Paleozoic; Logan et al., 2000). The Stikine assemblage contains the products of multistage arc magmatism and marine sedimentation as young as Middle Permian (Gunning et al., 2006). It is unconformably overlain by Triassic arc and marine sedimentary strata of the Stuhini Group. Above a Late Triassic-Early Jurassic unconformity, the Hazelton Group and its intrusive sources (latest Triassic to Middle Jurassic) represent the final stage of island arc magmatism and its aftermath. Unconformably above the Hazelton Group, the Bowser Lake Group (Middle Jurassic to Lower Cretaceous) is a northeasterly-sourced, southwestward-younging clastic overlap sequence derived from the collision of the Intermontane terranes and the edge of ancestral North America (Evenchick et al., 2007).

The Hazelton Group is distributed throughout most of Stikinia, around the margins of the Bowser basin (Fig. 2; Tipper and Richards, 1976). The lower Hazelton Group (latest Triassic to Early Jurassic; 205-185 Ma) records successive pulses of arc volcanism. Basal units are generally coarse, immature, locally-derived conglomerates and volcanic breccias. Regionally, thick sections of coarse conglomerates and olistostromal units (Ash et al., 1997a) suggest significant relief and syndepositional uplifting of source rocks (Greig, 1992). The upper Hazelton Group (Pleinsbachian to Callovian; ~ 190-161 Ma) consists of mainly post-arc sedimentary and minor volcanic strata (Gagnon et al., 2012), except for the Iskut River Formation, the bimodal volcanosedimentary fill of the Eskay rift in western Stikinia (Alldrick et al., 2005; Gagnon et al., 2012), and felsic tuffs in the southwestern part of the terrane, which represent a reconfigured, post-accretionary arc axis.

The subduction geometry of the Hazelton arc or arcs has long been debated. Unlike the contemporary Nicola-Takla arc of Quesnellia, which is characterized by a narrow, linear arc axis that migrated sequentially eastward from Late Triassic through Early Jurassic time (Logan and Mihalynuk, 2013 in press), in Stikinia, arc volcanism is thought to have occurred continuously or at least sporadically throughout the terrane, at present over a width of about 500 km (Marsden and Thorkelsen, 1992).This extent exceeds any reasonable width of a single magmatic arc; therefore it is likely that the Hazelton Group was fed by the products of two separate, possibly opposing arcs, similar to the modern Philippines (Marsden and Thorkelsen, 1992).

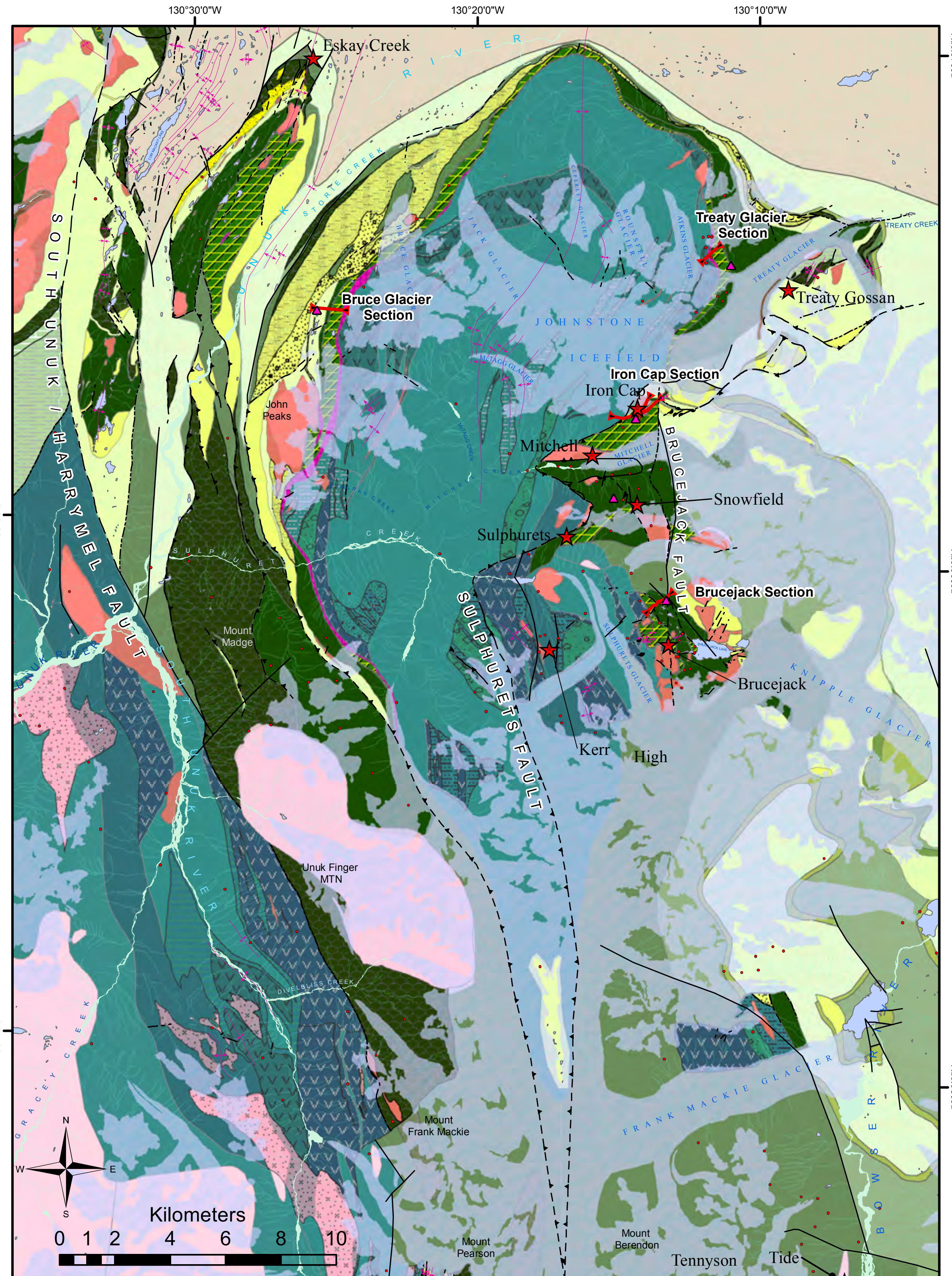


Fig. 4. Detailed geological map of KSM-Brucejack area and McTagg anticlinorium, and section locations. Compiled from Lewis (2013); additional sources MacIntyre et al. (1994), Evenchick et al. (2002).

Legend

Stratified Rocks

Quaternary

- Edziza volcanic rocks

Cretaceous - Upper Jurassic

- Bowser Lake Group undivided

JURASSIC

Hazelton Group

- Volcanic and sedimentary rocks undivided

Volcanic Rocks

- Volcanic rocks undivided
- Felsic Volcanics undivided
- Coherent rhyolite, autoclastic breccia
- Variably welded felsic lapilli tuff
- Epiclastic felsic breccia and crystal tuff
- Andesitic- basaltic volcanic rocks
- Subareal calc-alkalic andesite and dacite flows, pyroclastic and epiclastics and lapilli tuff
- Pillow lavas, pillow breccias, interbedded mudstone and mafic volcanic rocks

Sedimentary rocks

- Sedimentary rocks undivided
- Limestone
- Calcareous sandstone
- Turbiditic mudstone - siltstone
- Intercalated sedimentary rocks
- **Jack Formation** Sandstone, siltstone, mudstone, wacke, tuff; Intermediate grey-green, beige and maroon, very fine to coarse grained, thin to thickly bedded, arkosic arenites, lesser quartz, graded in part, minor fossils.
- **Basal Jack Formation** Polymictic conglomerate with well rounded clasts of mainly (70%) felsic to intermediate intrusive rocks. Intrusive clasts are generally plagioclase-hornblende-phyric and crowded plagioclase porhyries with tonalitic to granodioritic compositions. Common intraclasts of black argillite (10%). Minor clasts of white polycrystalline quartz (10%), andesite (5%), siltstone + tuff (3%), gossanous quartz-sericite-pyrite replaced clasts (1%) and carbonate (1%). Quartz-rich arkoses and pebbly arkoses. Isolated basal carbonaceous mudrocks.

TRIASSIC

Stuhini Group

- Undivided volcanic and sedimentary rocks

Volcanic Rocks

- Intermediate volcanic rocks
- Mafic volcanic rocks
- Andesite boulder conglomerate

Sedimentary Rocks

- Sedimentary rocks undivided
- Limestone and Marble
- Argillite, siltstone turbidites, sandstone and wacke
- Arkosic sandstone, siltstone, mudstone
- Arkosic sandstone, tuffaceous polylithic conglomerate

Intrusive Rocks

- **Eocene** Coast Plutonic Suite
- **Early Jurassic** Texas Creek Plutonic Suite
- **Paleozoic** Stikine Pluitonic Suite

- MINFILE
- significant deposit
- 2013 flycamp
- section lines
- rivers
- lakes
- glaciers

Faults

Type

- defined
- approximate
- inferred

Motion

- normal
- thrust
- strike slip

Structure Lines

- antiform, upright
- synform, overturned
- synform, upright

4. Geology of the Treaty Glacier-KSM-Brucejack trend

4.1. Local subdivisions of the Hazelton Group: history and present usage

Grove (1971; reprinted in 1986) and Alldrick (1993) mapped the area between Stewart and Frank Mackie Glacier at a 1:50,000 scale. Grove's subdivision of the Hazelton Group into the Unuk River, Betty Creek, and Salmon River formations was modified by Alldrick (1993), who recognized six subunits of the Unuk River Formation and introduced the Mt. Dilworth Formation, a dacitic unit that separates the mainly sedimentary Salmon River Formation from the underlying Betty Creek Formation near the Mt. Dilworth syncline in the vicinity of the Big Missouri and Premier deposits (Fig. 3; Table 1). This stratigraphic scheme was extended northward during mapping of the Sulphurets, Unuk River, and Snippaker areas (Alldrick and Britton, 1988, 1991; Alldrick et al. 1989; Alldrick and Britton, 1992; Alldrick et al., 1990).

According to Lewis (2013; Table 1) the lower Hazelton Group includes a basal sedimentary unit of polymictic conglomerate, arkosic sandstone, and mudstone (Jack Formation) that is overlain by discontinuous volcanosedimentary units in the Betty Creek Formation (Unuk River, Brucejack Lake and Treaty Ridge members). The Salmon River Formation overlies Betty Creek Formation units and includes the Troy Ridge, Eskay, Bruce Glacier, and John Peaks members. We adhere to the nomenclature proposed by Lewis (2013) except in the case of the Salmon River Formation, which has been superseded by the Iskut River Formation in the Eskay rift and the Quock Formation elsewhere (Table 1; Gagnon et al., 2012).

4.2. Structure

To the east and south of Eskay Creek mine, including the Treaty-Stewart trend, the principal structures resulted from mid-Cretaceous sinistral transpression during development of

Table 1. Historical and current stratigraphic nomenclature for the Hazelton Group in the Treaty-Stewart-western Iskut region.

Series	Stage	ages (U-Pb range)	Alldrick, 1993	Lewis, 2013	Gagnon et al., 2012		This study	
Middle Jurassic	Bajocian	172-178 Ma	Salmon River Formation	Salmon River Formation • Bruce Glacier member • Troy Ridge member • John Peaks member • Eskay member	in Eskay rift: Iskut River Formation	outside Eskay rift: Quock Formation	in Eskay rift: Iskut River Formation • Bruce Glacier member • John Peaks member • Eskay member	outside Eskay rift: upper Hazelton Group (includes Troy Ridge member, Treaty Ridge member)
	Aalenian							
Lower Jurassic								
	Toarcian Pleinsbachian		Mt. Dilworth Formation	Betty Creek Formation • Unuk River member • Brucejack Lake member • Treaty Ridge member	Betty Creek Formation		Betty Creek Formation • Unuk River member • Brucejack Lake member	
			Betty Creek Formation					
	Pleinsbachian Sinemurian Hettangian	Brucejack: 194-186 Ma Unuk: 194-192 Ma	Unuk River Formation		Unuk River Formation			
				Jack Formation	Jack Formation		Jack Formation	
Upper Triassic		215-225 Ma	Stuhini Group	Stuhini Group	Stuhini Group		Stuhini Group	

The richly mineralized area between Eskay Creek and the Kerr-Sulphurets-Brucejack camp has been studied in detail for the last 40 years. Notable contributions, other than Alldrick and colleagues, include Henderson et al. (1992), Kirkham and Margolis (1995), Lewis et al. (2001) and a new 1:50,000 compilation map (Lewis, 2013). Understanding of Hazelton stratigraphy in the area has been strengthened by fossil collections and U-Pb ages (compiled by Lewis et al., 2001).

the Skeena fold and thrust belt (Fig. 3; Kirkham and Margolis, 1995; Lewis, 2013). Farther west, the South Unuk-Harrymel and Forrest Kerr faults show evidence of earlier origins. They are steep, major, north to north-northwesterly normal, east-side-down faults that bound the Iskut River Formation to the west, and by definition, the Eskay rift (Fig. 3). They underwent sinistral motion in mid-Jurassic time (~ 172 Ma; Lewis, 2001a), roughly coeval with opening of the rift and eruption of bimodal Iskut River Formation volcanic rocks (~ 175 Ma). Exposures west of these faults are at a comparatively deep level, predominantly Paleozoic Stikine assemblage and Stuhini Group with patchy Hazelton cover (Fig. 3). North-south alignment of Devonian-Mississippian plutons immediately west of the Forrest Kerr fault (Fig. 3) may have been controlled by pre-existing structures (Logan et al., 2000).

East of the South Unuk-Harrymel fault, strata of the Stuhini, Hazelton, and Bowser Lake groups were deformed as part of the Skeena fold and thrust belt into a series of north- to northeast-trending folds with strongly curvilinear hinges that produced local culminations such as the McTagg anticlinorium and Eskay anticline (Fig. 3). The McTagg anticlinorium is a north-trending Cretaceous structural culmination that forms the western boundary of thick lower Hazelton Group exposures (Fig. 3). All Hazelton Group units thin markedly across the axis of the anticlinorium (Figs. 3, 4; see also Lewis, 2013), suggesting that it persisted as a high-standing block during the Early Jurassic. It is bounded in part by thrust faults that verge away from its hinge, particularly the east-vergent Sulphurets fault (Figs. 4, 5). The Kerr-Sulphurets-Mitchell-Iron Cap system forms a single northerly band of alteration in the immediate footwall of the Sulphurets thrust. The Mitchell thrust is a prominent footwall splay of the Sulphurets thrust that separates the Snowfield and Iron Cap zones in its hanging wall from the Mitchell zone in its footwall (Fig. 4). The Eskay anticline is cored by the Middle Jurassic host sequence of the Eskay Creek VMS deposit.

In addition to the South Unuk fault, Grove (1986, his fig. 13) outlined a north-trending zone of high strain, the Cascade Creek shear zone, along the Granduc Road in the Stewart camp east of the Salmon Glacier (Fig. 3). This fault was interpreted by later workers as a zone of north-trending mid-Cretaceous folds such as the Mt. Dilworth syncline (Alldrick, 1993) and east-vergent thrust faults (Ascot Resources, unpublished 2013), rather than a zone of mylonitization or shearing. It is probably better termed the Cascade Creek deformation zone (Fig. 3). It is expressed as a concentration of northerly faults in the vicinity of the Premier and Big Missouri mines.

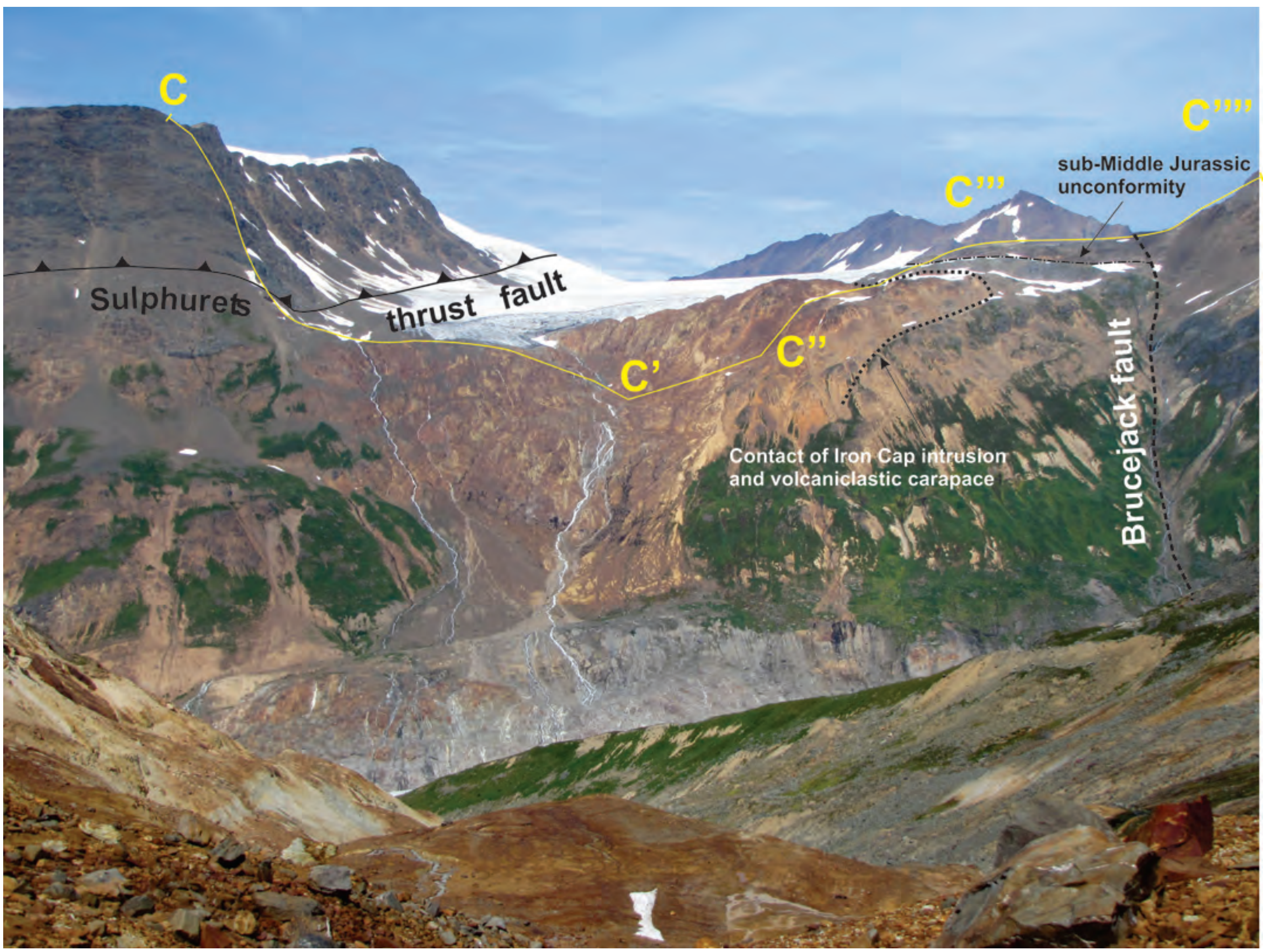


Fig. 5. Looking north from the Snowfield zone across the Mitchell Glacier to the Iron Cap zone and structurally higher Sulphurets fault. C-C'-C''-C''' refers to section presented in Figure 16.

5. Stratigraphy and sedimentology of the Jack Formation (basal Hazelton Group)

We examined the Jack Formation at four sections on the margins of the McTagg anticlinorium: Bruce Glacier, Treaty Glacier, Brucejack, and Iron Cap (Fig. 4). We also studied a fifth section of basal Hazelton Group at the Tide-Tennyson prospect south of the McTagg anticlinorium (Fig. 4).

5.1. Bruce Glacier section

The Bruce Glacier section is in a west-younging, overturned panel west of the McTagg anticlinorium (Fig. 4). It exposes rocks from beneath the unconformity between the Stuhini Group and Jack Formation, across the entire Jack Formation, and into the unconformably overlying Bruce Glacier member (Fig. 6; Lewis, 2013). The basal unconformity cuts at a low angle (< 15^{o}) through a Stuhini Group section of polymictic conglomerate, pillow basalt and pillow breccia (Fig. 6). It truncates units within the Stuhini Group at a regional scale (Fig. 4). Weak foliation and minor shears in the uppermost Stuhini Group are truncated at the unconformity and greenschist-grade mineral assemblages in the Stuhini Group (chlorite-epidote-actinolite) are lacking in the Jack Formation. The unconformity is a smooth surface with minimal relief.

We recognize four facies in the Jack Formation at the Bruce Glacier section: basal conglomerate; lower mudstone ± sandstone and siltstone; volcaniclastic; and upper mudstone ± sandstone and siltstone.

5.1.1. Basal conglomerate facies

The base of the Jack Formation consists of an 0.8 metre-thick felsic clast-bearing granule conglomerate, which is overlain by 100 metres of polymictic conglomerate containing rounded cobbles and boulders of felsic intrusive and volcanic rocks and quartz in an arkosic matrix (Fig. 7a). The low percentage (< 2%) of clasts (Fig. 8) derived from subjacent Stuhini Group is remarkable. Clasts are well rounded, and moderately to highly spherical. Angular black mudstone intraclasts occur singly and as clusters throughout the facies (Fig. 7b). Several kilometres north of the section, between the Bruce and Jack glaciers (414251 E, 6271398 N), black carbonaceous mudstones occur at the base of the Jack Formation, below the lowest conglomerate.

The conglomerate thickens and coarsens south of the line of section: two kilometres to the south, the largest tonalite clast is 2 metres in diameter (Fig. 7c). At that locality, conglomerate matrix varies from black mudstone to arkose. To the south

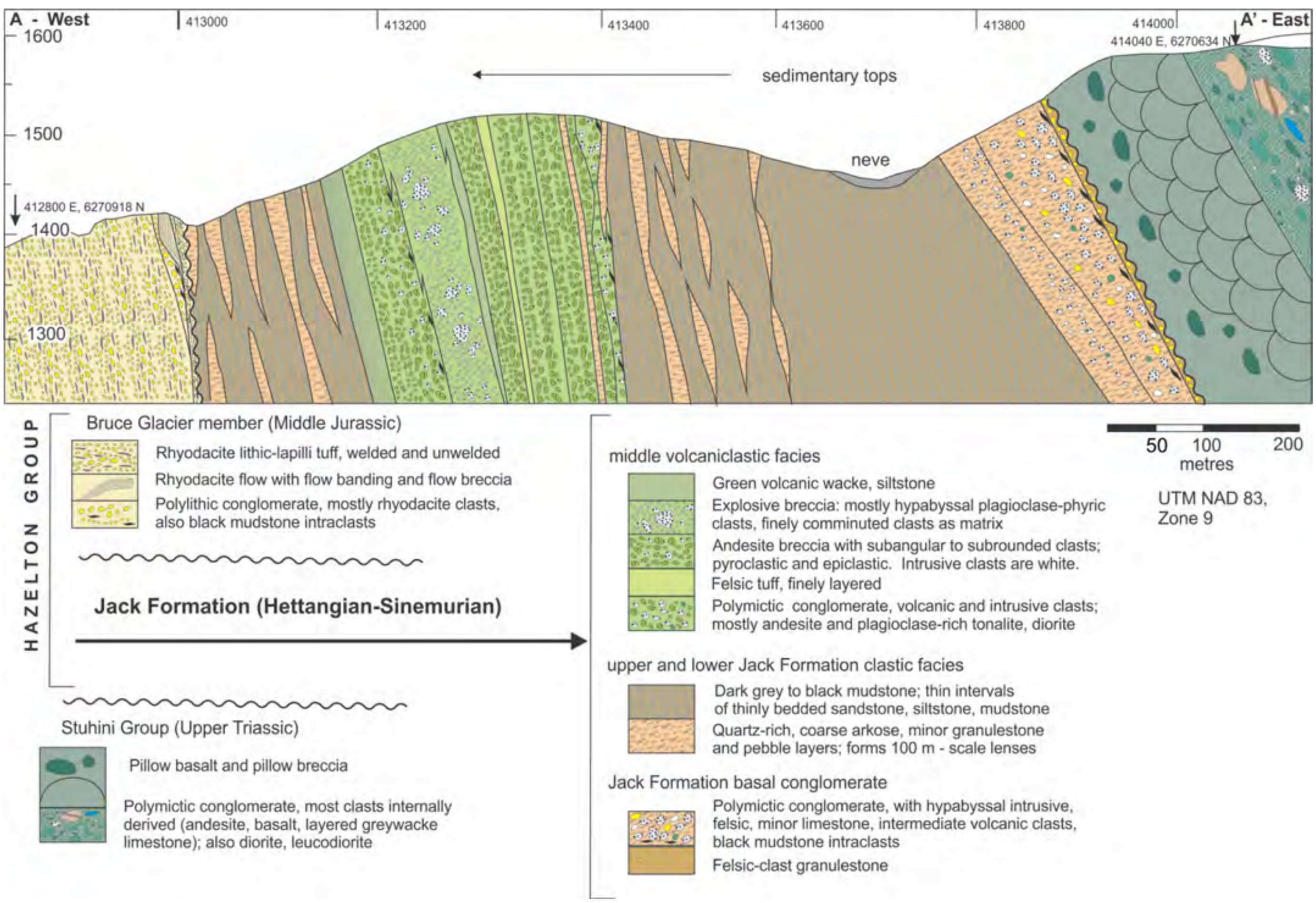


Fig. 6. Bruce Glacier section.

Fig. 7. Jack Formation siliciclastic units, Bruce Glacier section. **a)** Basal polymictic conglomerate, 413850 E, 6269040 N. **b)** Concentration of angular, tabular, black mudstone intraclasts at base of conglomerate bed, likely ripped up from underlying black mudstone layer; near base of Jack Formation, 414404 E 6271697 N. **c)** Large boulder of tonalite in basal conglomerate. Note other round intrusive cobbles (white outlines), 413875 E, 6268846 N. **d)** Thinly-bedded calcareous siltstone, fine-grained sandstone and carbonaceous mudstone, mudstone ± sandstone and siltstone facies. Cross-beds show paleocurrent to west (toward bottom of photo), 413557 E, 627708 N. **e)** Quartz-rich coarse sandstone, typical of sandstone lenses in mudstone facies, 413567 E, 6270704 N.

(413818 E, 6269809 N) beneath the lowest conglomerate, laminated to thinly bedded fine-grained volcanic sandstones rest unconformably on sheared Stuhini andesite conglomerate. These beds were probably locally derived from immediately underlying Stuhini Group.

Isolated exposures of fine-grained rocks beneath the basal conglomerate, and the ubiquitous presence of black mudstone intraclasts in coarse clastic units, suggest that basin initiation

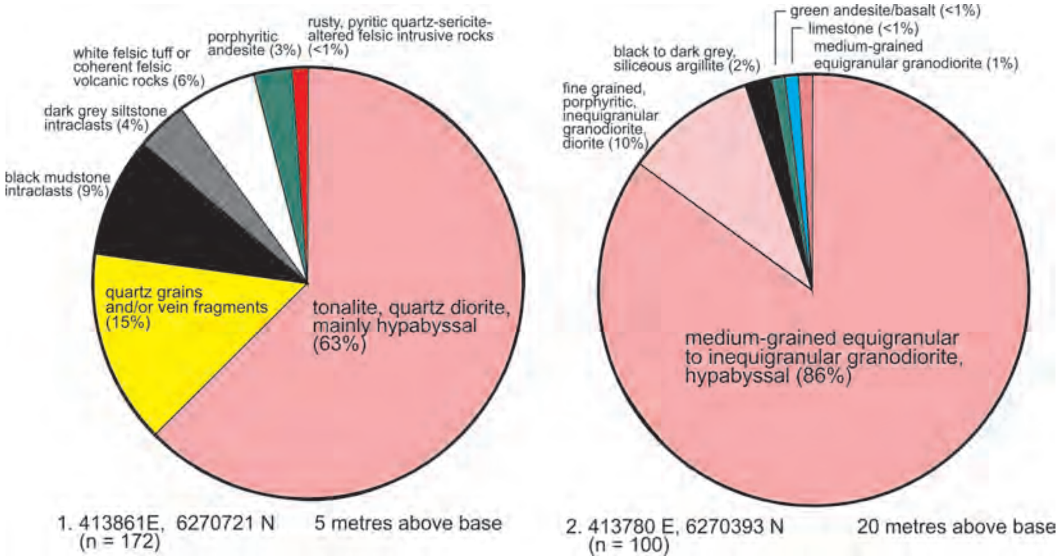


Fig. 8. Clast counts from basal Jack Formation conglomerates in the Bruce Glacier area.

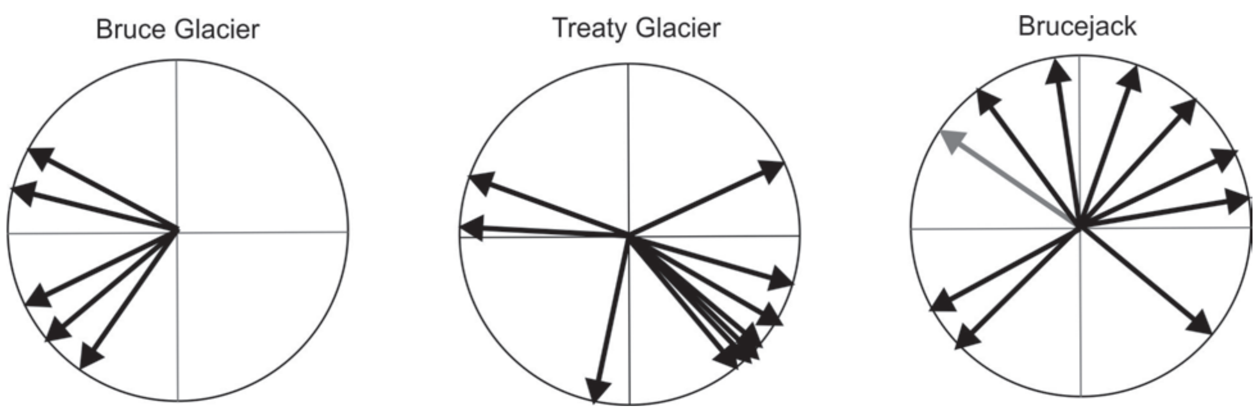


Fig. 9. Jack Formation paleocurrents; measurements corrected for tilted bedding. Grey arrow for Brucejack Lake section is from olistostromal block.

was marked not by an influx of coarse debris, but quiet water sedimentation in a standing body of water. Thick sections of cobble-boulder conglomerate imply later influx of debris from a relatively nearby area of high relief.

In its upper 40 metres, the basal conglomerate fines upwards to thick-bedded quartz-rich arkose with scattered pebbles and granules. Its top is abrupt, passing into mudstone over a few metres.

5.1.2. Lower mudstone ± sandstone and siltstone facies

Predominantly mudstone intervals are exposed both above the basal conglomerate facies and in the upper part of the Jack Formation (Fig. 6). The lower succession is about 400 m thick. The mudstones are carbonaceous, laminated to thinly bedded, and lack evidence of bioturbation. They are interrupted by cm- to dcm-scale layers of sandstone with rare cross stratification and siltstone (Fig. 7d). The sandstones are cemented by carbonate (calcite-ferrodolomite), which weathers bright orange. Lenticular beds of sharp-based, very coarse-grained quartz-rich arkose to arkosic granulestone (Fig. 7e) are scattered in the upper half of the interval. These beds are typically 10 to 20 metres thick and can be traced laterally for about 100 metres. They show sharp, erosive bases with scours, and graded tops. Other sedimentary structures are sparse, except subtle internal bedding. Black mudstone intraclasts and polymictic pebble layers are concentrated at the base of many beds, but can be scattered throughout.

The lower mudstone ± sandstone and siltstone facies grades to the volcaniclastic facies through a transition in which quartz-rich sandstone and pebbly beds interfinger with beds containing andesite and diorite clasts. Furthermore, local beds of arkose, siltstone, and mudstone, similar to those in the predominantly mudstone facies are found in the volcaniclastic facies, emphasizing a gradational boundary.

The carbonaceous mudstones likely represent quiet water sedimentation (below wave base) in an anoxic standing body of water. Coarse interbeds are likely subaqueous mass flow deposits that punctuated background fine-grained sedimentation. Five cross bedding measurements from fine-grained sandstones in the lower and upper mudstone units indicate southwesterly to west-northwesterly paleocurrents (Fig. 9), away from the area now occupied by the McTagg anticlinorium.

5.1.3. Volcaniclastic facies

Most of the volcaniclastic facies consists of matrix-supported andesitic-hypabyssal porphyry breccias (Fig. 10a). In contrast to conglomerates lower in the section, clasts are almost exclusively of andesite and porphyritic diorite. Black mudstone intraclasts occur in some beds (Fig. 10b). The breccias define thick (15-30 m) unstratified to poorly stratified depositional units; in most cases the distinction between a pyroclastic or epiclastic origin cannot be made. However, one breccia unit contains angular clasts (± jig-saw fit) of crowded plagioclase-porphyry in a fine-grained matrix that includes ~ 50% broken plagioclase crystals (Figs. 6, 10c), suggestive of an origin by phreatic explosion.

Although predominantly consisting of cobble and block breccias and conglomerates, the volcaniclastic facies contains local beds of coarse-grained quartz-rich arkose, siltstone, and mudstone, and one interval of laminated to thinly bedded felsic tuff (Figs. 6, 10d). Over an interval of 25 metres at the top of the unit, coarse andesitic breccia and conglomerate grade upward through green volcanic wacke to coarse-grained quartz-rich arkose and grey argillite. This interval is overlain by dark grey to black mudstone of the upper siliciclastic unit. Transitional upper and lower boundaries suggests that the volcaniclastic facies is an integral part of the Jack Formation (rather than Unuk River member, cf. Lewis, 2013).

The appearance of pyroclastic beds and coarse volcanic-derived detritus indicates that an episode of andesitic volcanism interrupted the background quiet-water sedimentation indicated by the underlying and overlying predominantly mudstone units.

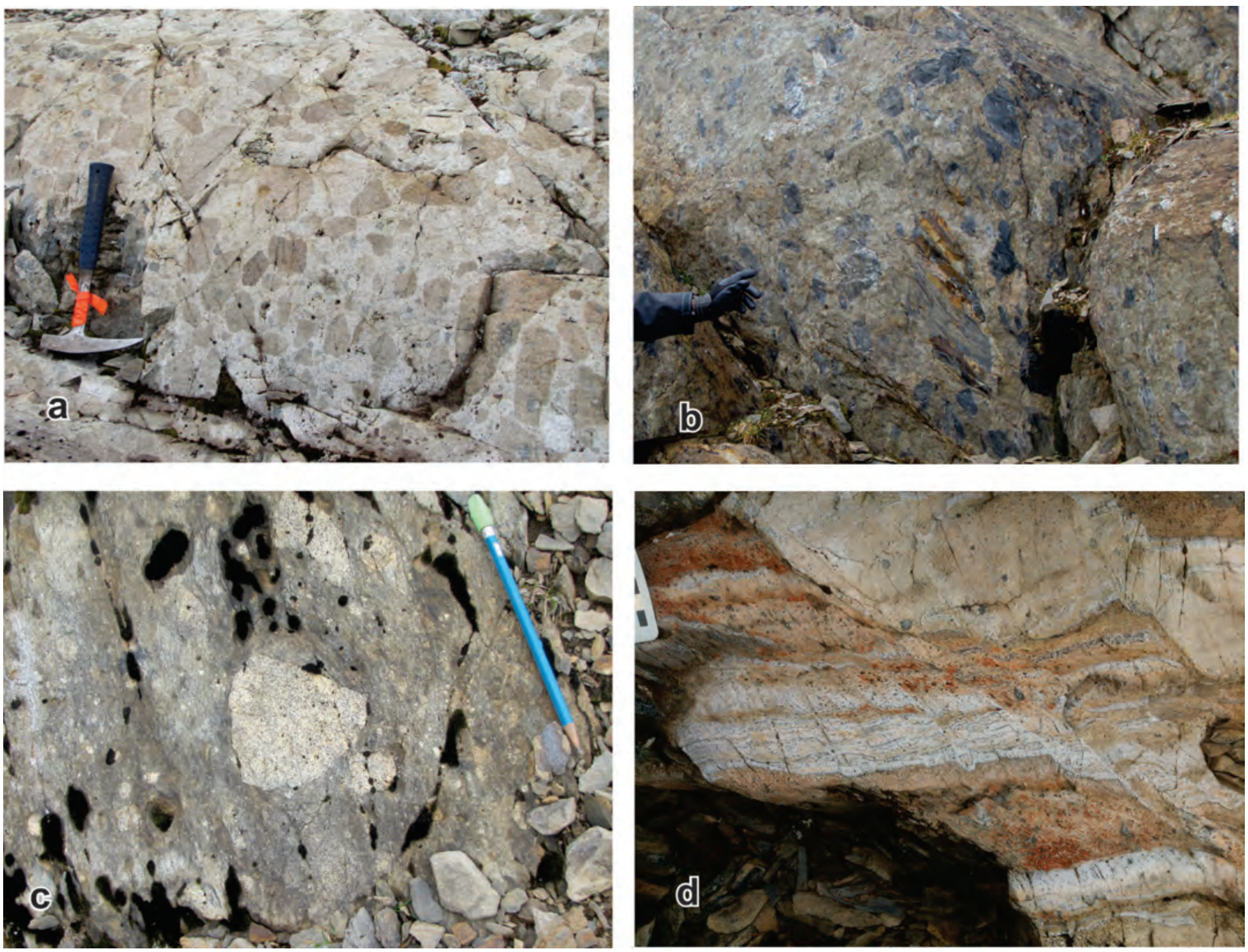


Fig. 10. Jack Formation volcaniclastic units, Bruce Glacier section. **a)** Andesite block breccia from volcaniclastic facies, 413278 E, 6270599 N. **b)** Concentration of black mudstone intraclasts near base of volcanic breccia bed. 413145 E, 6370655 N. **c)** Monolithologic crowded plagioclase porphyry-clast explosion breccia from volcaniclastic facies, 413200 E, 6270667 N. **d)** Small-scale penecontemporaneous normal faults (with overstepping relationships and sediment smeared along fault surfaces) in thinly bedded felsic tuff, 413929 E 6270547 N.

5.1.4. Upper mudstone ± sandstone and siltstone facies

This facies is identical in character and clast composition to the lower predominantly mudstone interval, except that lenticular coarse layers are scattered throughout, and conglomeratic beds in the coarse-grained lenses are sparser and finer grained. Although Lewis (2013) assigned this facies to the Betty Creek Formation, based on its stratigraphic position above the interpreted Unuk River member, we include it in the Jack Formation because of its close resemblance to the lower mudstone-sandstone-siltstone unit. It is abruptly overlain by felsic volcaniclastic rocks of the Bruce Glacier member (upper Hazelton Group, Middle Jurassic, ~ 173-176 Ma; Lewis, 2001b). Although paraconformable along the line of the section, the base of the upper Hazelton Group bevels downsection through the lower Hazelton sequence from south to north along the western side of the McTagg anticlinorium (Lewis, 2013). This upper mudstone unit represents a return to quiet water sedimentation following an episode of andesitic volcanism.

5.2. Treaty Glacier section

The Treaty Glacier section, on the northeastern nose of the McTagg anticlinorium, follows a northeast-trending ridge between the Treaty and Atkins glaciers (Fig. 4). The section extends from the Stuhini Group to the base of the paraconformably overlying Unuk River member of the lower Hazelton Group (Lewis, 2013). The base of the section is in the Stuhini Group at the "Mama Susu A" showing, where it consists of andesite block breccia, polymictic conglomerate, thinly to medium-bedded litharenite, and dark grey argillite (Fig. 11). Compared to the Jack Formation, the volcanic rocks are relatively primitive (andesites have augite rather than hornblende) and the sedimentary rocks are compositionally immature (sandstones are quartz deficient). Load casts and argillite intraclasts are present in the sandstones. As in the Stuhini Group at the Bruce Glacier section, but in contrast to mudstone rip-up clasts in the Jack Formation, sedimentary clasts in the polymictic conglomerates consist of multiple sandstone-siltstone-argillite beds, indicating reworking of a previously lithified section. The basal unconformity of the Jack

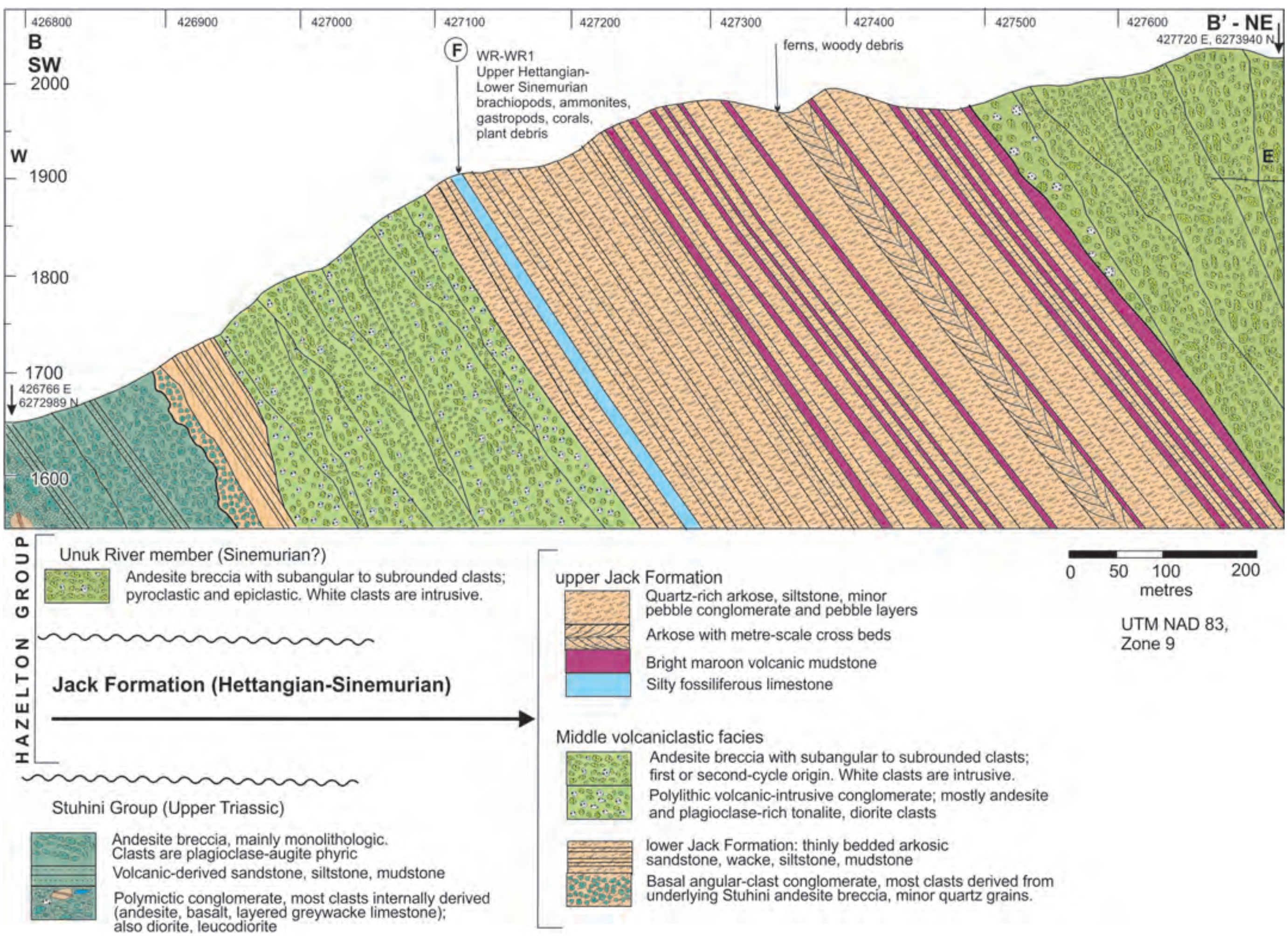


Fig. 11. Treaty Glacier section.

Formation cuts across underlying bedding at a high angle. The unconformity is a jagged, highly irregular surface at decimetre to metre scale (Fig. 12a). Four Jack Formation facies are developed at the Treaty Glacier section: basal conglomerate; arkose, siltstone, and mudstone; volcaniclastic; and arkose, tuffaceous mudstone ± limestone.

5.2.1. Basal conglomerate facies

Above the unconformity is a 20-m section of locally-derived, clast-supported (siltstone matrix) sharpstone conglomerate. Clasts are from the underlying Stuhini Group and include dark grey argillite and siltstone, dark green and maroon andesite, and crowded porphyry. The conglomerate contains a carbonate-Fe-oxide cement.

5.2.2. Arkose, siltstone, and mudstone facies

Above the basal conglomerate is a drab, olive-green unit of arkose, siltstone, and thinly bedded mudstone. Thickness of this unit varies locally from 80 metres to only a few metres, due to downcutting beneath the overlying volcaniclastic facies. The absence of black, carbonaceous mudstone in this facies is notable, compared with the Bruce Glacier section.

5.2.3. Volcaniclastic facies

The volcaniclastic unit is about 250 metres thick and, similar to rocks at the Bruce Glacier section, consists mainly of thickly bedded conglomerates and breccias that contain volcanic and intrusive clasts. Some beds contain matrix-supported angular to subangular andesite clasts with subordinate intrusive clasts. Others, particularly near the top of the unit, are polymictic clast-supported conglomerates in which intrusive clasts (plagioclase-hornblende porphyry, hornblende diorite and monzodiorite, quartz monzonite, and crowded plagioclase porphyry) are more abundant than volcanic clasts. The polymictic conglomerates also contain clasts of andesite, dark grey mudrock, and pale green tuff. As at the Bruce Glacier section, it fines upward and passes transitionally into the overlying succession, in this case a unit of arkose and volcanic mudstone with one bed of limestone.

5.2.4. Arkose, tuffaceous mudstone ± limestone facies

The upper 500 metres of the Treaty glacier section consist predominantly of interbedded arkose and maroon tuffaceous mudstone (Fig. 13). Sedimentary structures include interference ripples (~ 100 m upsection from the base of the unit, Fig. 12b;), impressions of delicate fern fronds and woody debris (~ 325 metres above the base of the unit Fig. 12c), and m-scale trough cross stratification (Fig. 12d). Bedding in some of the cross-stratified beds is highlighted by single pebble layers. Paleocurrents, mainly derived from cross-bed measurements in the upper part of the facies, are polymodal, with southeasterly directions predominant (Fig. 9). Within a few metres of the base of the facies, argillaceous limestone and silty calcareous sandstone contain a rich shelly fauna of brachiopods, gastropods and ammonites (Fig. 12e). A macrofossil collection from this locality (WR-WR1; Lewis et al. 2001) is of Upper Hettangian to Lower Sinemurian age.

Maroon and green tuffaceous mudstones appear ~ 200 metres above the base of the section, along with a 60 centimetre-thick layer of green vitric lapilli tuff. The mudstones are interbedded on decimetre to metre scale with quartz-rich arkoses that have a maroon tuffaceous matrix (Fig. 13). The arkoses contain maroon and green fine-grained volcanic pebble layers; some are cross-stratified. The absence of black carbonaceous mudstone beds and intraclasts in this mudstone-rich section is noteworthy, considering their abundance in siliciclastic facies at the Bruce Glacier section. Toward the top of the section, the number and thickness of mudstone intervals increases (Fig. 11), indicating a progressive increase in nearby volcanic activity.

A succession of bright maroon tuffaceous mudstones with thin, sparse arkose interbeds forms the uppermost 50 metres of the facies. It is overlain by the basal Unuk River member, a 10-20 metre-thick unit of matrix-supported polymictic conglomerate containing subrounded to subangular clasts of monzonite, pink syenite, maroon crystal tuff, and pink rhyodacite (Fig. 12f). The conglomerate is overlain by a thick section of andesite block breccias, bomb breccias, and heterolithic andesite-hypabyssal clast breccias. Shown as over 2 kilometres in mapped width (Lewis, 2013), and given local dips, this andesitic section is probably 1.25 to 1.5 kilometres thick.

The transition from the volcaniclastic facies to rocks of the arkose, tuffaceous mudstone ± limestone facies represents the cessation of relatively proximal andesitic volcanism and the establishment of a shallow-marine depositional environment. Initial carbonate sedimentation (with shallow-water fauna) was overwhelmed by siliciclastic input. Interference ripples, polymodal paleocurrents, and fern imprints suggest a shoreface environment.

5.3. Brucejack section

The Brucejack section is about 1.5 kilometres northwest of Brucejack Lake, east of the McTagg anticlinorium (Fig. 4). It extends northeasterly from near the top of the Stuhini Group, through a comparatively thin section of Jack Formation and into an overlying andesitic pyroclastic sequence assigned to the Unuk River member by Lewis (2013). The section forms a northeast-younging panel that is truncated by the Brucejack fault (Fig. 14). We recognize three facies: basal conglomerate; sandstone megaclast-bearing mudstone; and volcaniclastic.

The Stuhini Group in this section is similar to that at Treaty and Bruce Glaciers, in that it generally comprises interbedded, compositionally monolithologic but texturally polylithic, mainly andesite breccias, and polymictic conglomerates, arkosic sandstones and siltstones. A unique feature at this locality, however, is the presence of a thick polylithic breccia at the top of the Stuhini Group, in which fine-grained grey felsic clasts are more abundant than andesites. Such rocks in the Stuhini Group are a possible source for the grey to white felsic clasts in the Jack Formation.

Fig. 12. Treaty Glacier section photos. **a)** Stuhini Group-Jack Formation unconformity, showing small-scale rugged topography, in part controlled by fractures in underlying Stuhini Group. Jack Formation fills paleodepression; clasts mainly derived from immediately subjacent Stuhini breccia, 426997 E, 627040 N. **b)** Interference ripples marks on bedding surface, arkose, tuffaceous mudstone ± limestone facies, 427184 E, 6273417 N. **c)** Fern fronds in arkose, tuffaceous mudstone ± limestone facies. 427346 E, 6273592 N. **d)** Large-scale trough cross-beds in arkose, tuffaceous mudstone ± limestone facies, 427429 E, 6272976 N. **e)** Brachiopod from near base of arkose, tuffaceous mudstone ± limestone facies, 427114 E, 6273364 N. **f)** Basal conglomerate, Unuk River member, 427490 E, 6272920 N.

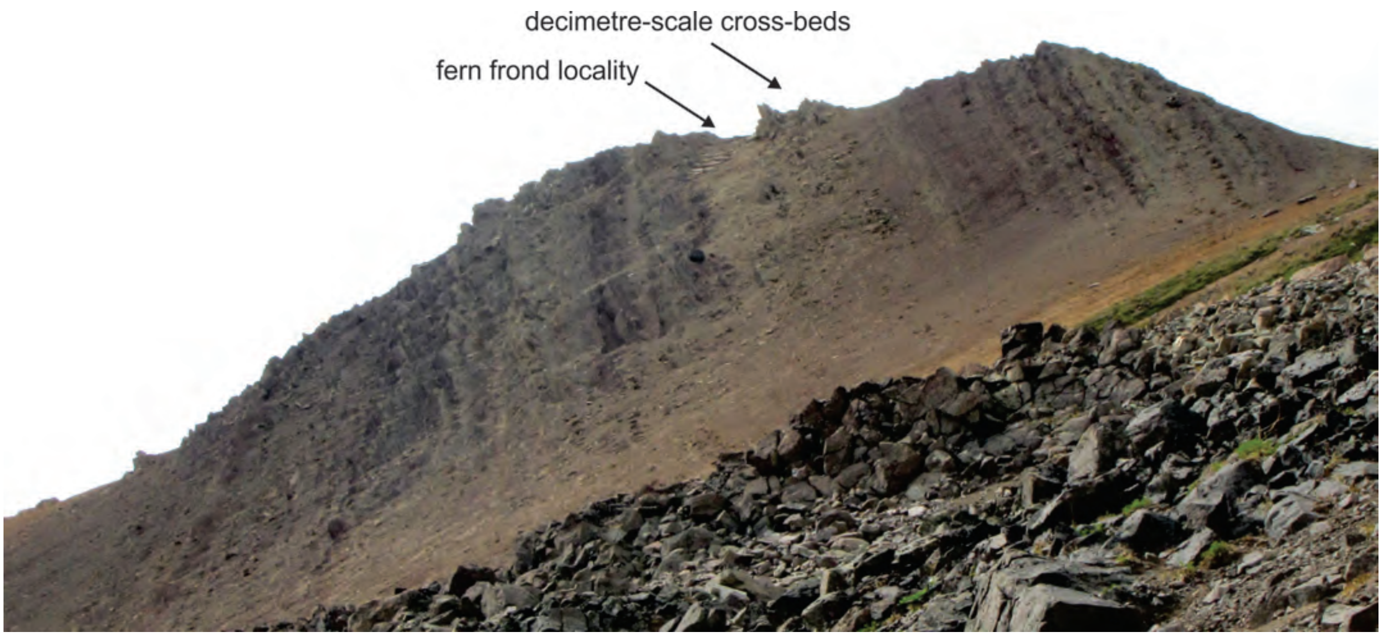


Fig. 13. View to the northwest of interbedded arkose and maroon tuffaceous mudstone in the upper part of Treaty Glacier section.

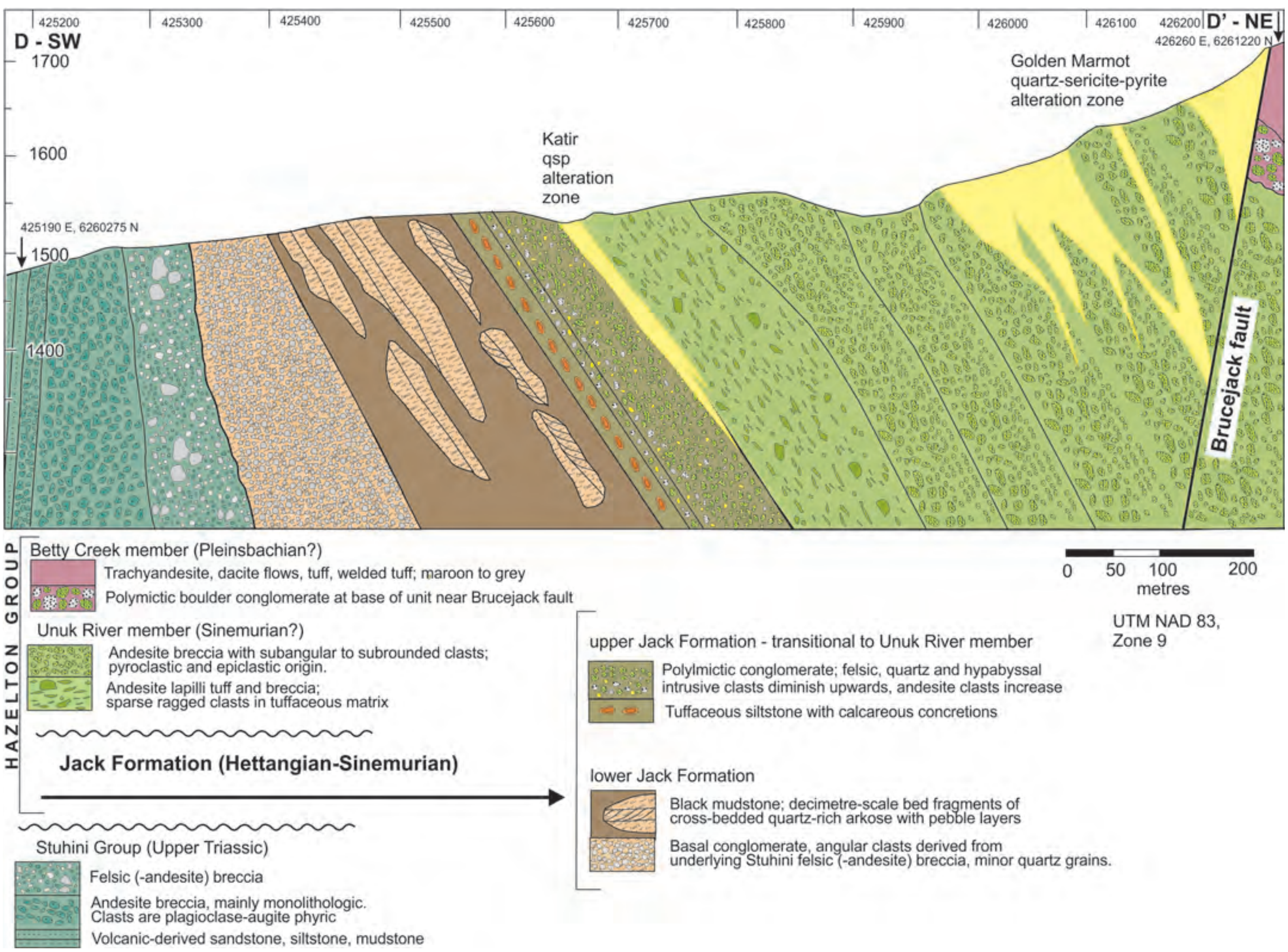


Fig. 14. Brucejack section.

5.3.1. Basal conglomerate facies

As at Treaty Glacier, the basal Jack Formation is a massive sharpstone conglomerate 80 metres thick containing mostly clasts derived from felsic and andesitic rocks in the immediately subjacent Stuhini Group. Unlike Stuhini Group conglomerates, those in the Jack Formation contain matrix quartz grains. The conglomerate is overlain abruptly by black carbonaceous mudstone.

5.3.2. Sandstone megaclast-bearing mudstone facies

Above the basal conglomerate facies is a 200 metre-thick section of carbonaceous mudstone that surrounds densely-packed, large (5-20 m scale) fragments of stratified and cross-stratified, coarse-grained (± pebbles), quartz-rich arkose and tuffaceous siltstone (Fig. 15a). Bedding attitudes in the blocks are concordant with the overall layering in the section. Mudstone penetrates block boundaries, creating marginal zones of in situ breccia (Fig. 15b), and stratification in the blocks is truncated at clast boundaries, indicating that the blocks are allochthonous and the unit an olistostrome. As elsewhere in the Jack Formation, pebbles in the blocks are of felsic high-level intrusions, fine-grained felsic volcanic rocks, and mudstone intraclasts. The nearest possible source for the blocks is an intact section of thickly-bedded and cross-bedded arkoses 500 metres to the southeast (Fig. 15c). Paleocurrents at this intact section are polymodal, with a slight tendency to northeasterly flow (Fig. 9). Along strike northwest of the section, the megaclast-bearing unit is replaced by bedded arkosic sandstone, siltstone, and mudstone. Above the megaclast-bearing unit is a transition from siliciclastic to volcaniclastic deposits. At the transition, a distinctive light green tuffaceous siltstone unit containing large (5-10 cm) concentrically coated calcareous concretions directly overlies the highest olistostrome (Fig. 15d).

The megaclast-bearing facies is significant to structural interpretations for this area. Because sands lack cohesion, preservation of large sandstone blocks indicate that previously deposited sands were deposited, buried, lithified, uplifted, and reworked as gravity slides into an environment accumulating muds, which is consistent with penecontemporaneous faulting.

5.3.3. Volcaniclastic facies

The concretionary layer is overlain by a 5-metre thick clast-supported polymictic conglomerate that contains clasts of hypabyssal crowded plagioclase-phyric intrusive rocks, and fine-grained felsic volcanic rocks in a quartz sand-rich matrix. This conglomerate also contains concretions reworked from the underlying siltstones (Fig. 15e). The conglomerate passes upward into quartz-rich coarse-grained sandstones and granulestones, and then to tuffaceous wacke with scattered concretions. Upward, juvenile andesite clasts increase in abundance over 50 metres, across the layer-parallel Katir quartz-sericite-pyrite alteration zone, which occupies a deep gully. From the northeastern side of the gully to the Brucejack fault, monolithologic andesite breccias form all of the section. Some of these contain ragged clasts with chilled margins (Fig. 15f), and are of pyroclastic origin. Other block and cobble breccias may be either pyroclastic or epiclastic deposits. The base of the Unuk River member is placed at the bottom of the andesitic breccias (Fig. 14).

5.4. Iron Cap section

The Iron Cap section is in the immediate footwall of the Sulphurets fault. It extends eastward from the centre of the Iron Cap intrusion, north of the Mitchell Glacier, to near the Brucejack fault (Figs. 4, 5). The base of the Jack Formation is not exposed; at the top of the section, a thin sequence of unaltered andesite breccia and arkosic granule-pebble conglomerate is unconformably overlain by the Treaty Ridge member (Middle Jurassic; Lewis, 2013).

The Iron Cap intrusion, part of the ~ 195 Ma Mitchell suite (Kirkham and Margolis, 1995) is the hornblende-plagioclase porphyry that hosts the Iron Cap porphyry Cu-Au deposit. Most of the section is in highly altered rocks of the intrusion (Figs. 16, 17). Our primary goal at this section was to document the relationship between the intrusion and the Jack Formation. Near the centre of the transect (west of C', Figs. 16, 17), the intrusion contains septa of quartz-bearing granule and pebble conglomerate (Fig. 18a). These septa, along with the porphyry, display silica-sericite-pyrite-alteration, demonstrating that the Iron Cap intrusion and porphyry deposit developed, at least in part, after Jack Formation deposition.

Near the eastern end of the transect, the intrusion passes into a thin, variable carapace of explosion breccia, andesite flows, pillowed flows and breccias, and very small felsic volcanic units (Figs. 5, 16, 17). The explosion breccia consists of crowded porphyritic hypabyssal monzodiorite clasts, derived from phases of the Iron Cap intrusion, along with irregularly-shaped, juvenile andesite clasts, in a finely comminuted rock matrix. Contact relationships show that the explosion breccia cuts the upper part of the intrusion, but also interfingers with extrusive andesite breccias (Figs. 16, 17). The limit of intense phyllic, texturally-destructive alteration corresponds approximately with the edge of the pluton, but extends into the explosion breccia, and to a lesser extent, into the overlying andesite unit. The andesite breccia, highly variable in thickness (from over a hundred metres south of the zone to less than ten metres along the section), passes upward into lapilli tuff and green, tuffaceous siltstone. Over less than ten metres these volcaniclastic units pass upward into dark grey mudstone and black mudstone intraclast-bearing, quartz-rich arkosic conglomerate and granulestone that are similar to siliciclastic units of the Jack Formation elsewhere (Fig. 18b). Lying above the andesitic extrusive carapace, these arkosic beds are unaltered, suggesting that they post-date development of the mineralized system.

Similar intimate relationships between Jack Formation deposition, intrusion, alteration and phreatic explosion breccias are exposed near the Snowfield zone, south of Mitchell Creek. There, a band of highly altered Jack Formation quartz-rich arkose lies in the main alteration zone (Fig. 19a), but in its

Fig. 15. Brucejack section. **a)** Arkose megaclast surrounded by black carbonaceous mudstone matrix; edge of decimetre-scale broken bed behind, sandstone megaclast-bearing mudstone facies, 425511 E, 6260571 N. **b)** Brecciated margin of arkose bed in sandstone megaclast-bearing mudstone facies, 425511 E, 6260571 N. **c)** Parallel-stratified and cross-stratified coarse-grained sandstone, on strike with sandstone megaclast-bearing mudstone facies. **d)** Tuffaceous siltstone with carbonate concretions, volcaniclastic facies, 425559 E, 6260553 N. **e)** Pebble conglomerate with well-rounded clasts of crowded plagioclase porphyry and felsic tuffs and reworked concentrically-zoned concretions, volcaniclastic facies, 425579 E, 6260573 N. **f)** Ragged-clast andesite lapilli tuff, base of Unuk River member; clasts have chilled rims, 422237 E, 6260255 N.

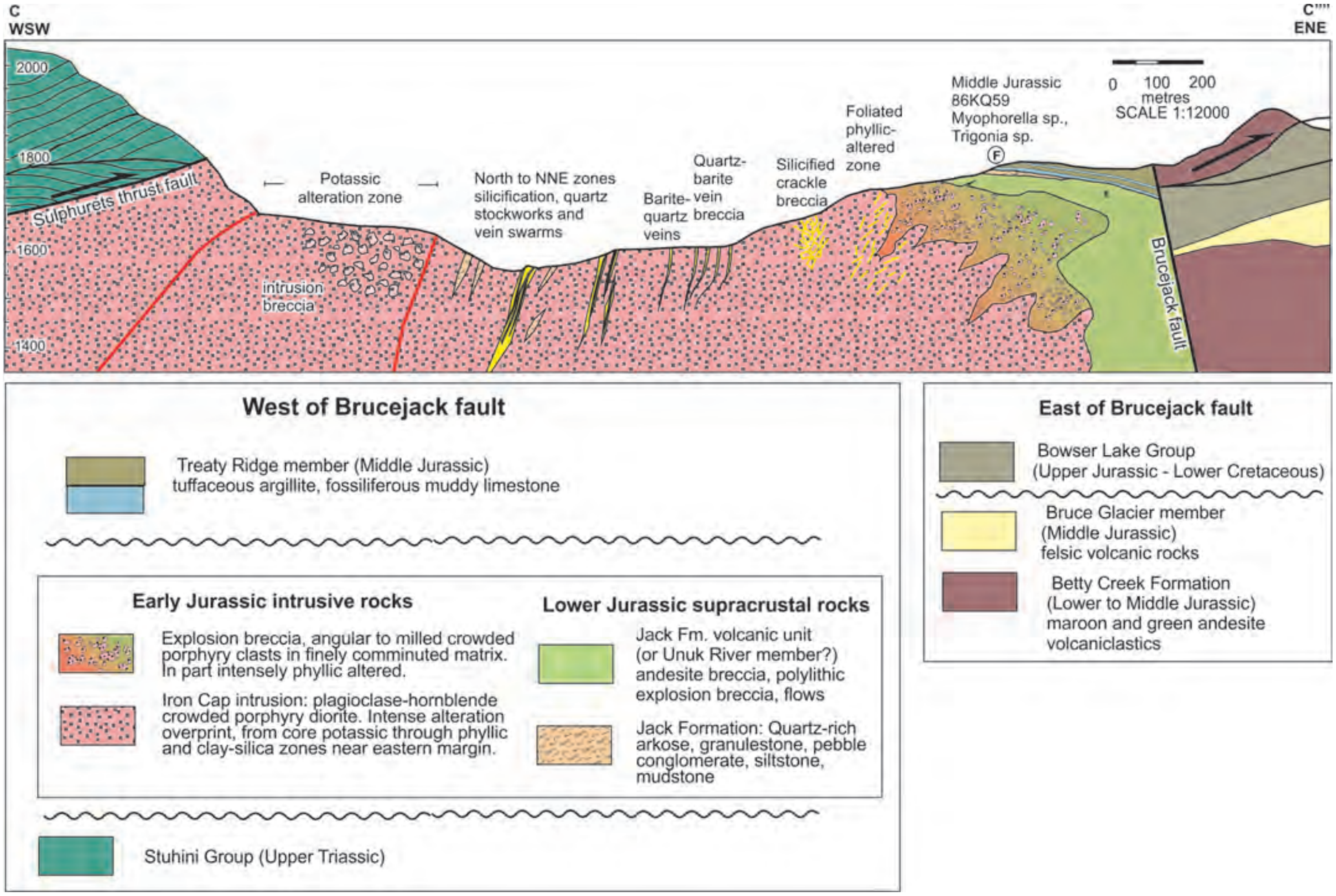


Fig. 16. Iron Cap section from Sulphurets fault to Brucejack fault; compare with panoramic photo in Figure 5.

western continuation outside the zone, unaltered Jack Formation conglomerates interfinger with plutonic-clast explosive breccias (Figs. 19b, c). Breccia dikes crowded with angular quartz clasts cut the Mitchell intrusion in the eastern part of the Mitchell zone (Fig. 20a, b). Surface eruption of breccias like these could have provided locally abundant polycrystalline quartz to the Jack Formation.

An isolated outcrop of tightly folded and strongly sheared black carbonaceous argillite and dark grey limestone is exposed 100 metres west of the section, approximately on strike with the andesite volcaniclastic to siliciclastic transition. Its relationship to the layered rocks of the section is unclear, but on the basis of rock type and deformation, it could be Stuhini Group. If so, the exposure might be the remains of a sub-Jack Formation paleohigh.

The highest Jack Formation clastic beds are overlain paraconformably by silty, fossiliferous limestone at the base of a sequence of interbedded tuffaceous siltstone and silty limestone (Figs. 5, 16, 17). A macrofossil collection from near this location (86KQ59, Lewis et al., 2001) yielded a Middle Jurassic age, which places it within the upper Hazelton Group (Table 1). The unit was assigned to the Treaty Ridge member of the Betty Creek Formation by Lewis (2013). However, it is similar in age and character to the Smithers Formation, part of the upper Hazelton Group in the Terrace-Smithers area (Gagnon et al., 2012). At this locality, either the higher pyroclastic and epiclastic units of the lower Hazelton Group were never deposited, or they were removed by erosion prior to the Middle Jurassic, and a prolonged hiatus (20 million years) separates the upper from the lowermost Hazelton Group. This unconformable relationship between the upper and lower Hazelton Group is equivalent to that seen on the west side of the McTagg anticlinorium.

5.5. Tennyson section south of Frank Mackie Glacier

Near the Tide-Tennyson prospect south of the McTagg anticlinorium (Figs. 3, 4), is a thick (> 500 m), coarse conglomerate with two 10 m interbeds of maroon pebbly mudstone (Fig. 21). The conglomerate contains clasts of andesite, basalt, black siliceous argillite, diorite, chert, quartz, limestone and silicified, cherty limestone. The clasts were derived from the Hazelton and Stuhini groups and, in the case of the limestone (Fig. 21a), possibly the Stikine assemblage (Permian Ambition Formation, Gunning et al., 2006). The clasts are angular to subrounded, have maximum diameters ranging from a few centimetres to several metres (average 20-50 cm), and are generally supported in a fine-grained matrix.

The maroon pebbly maroon mudstones have different

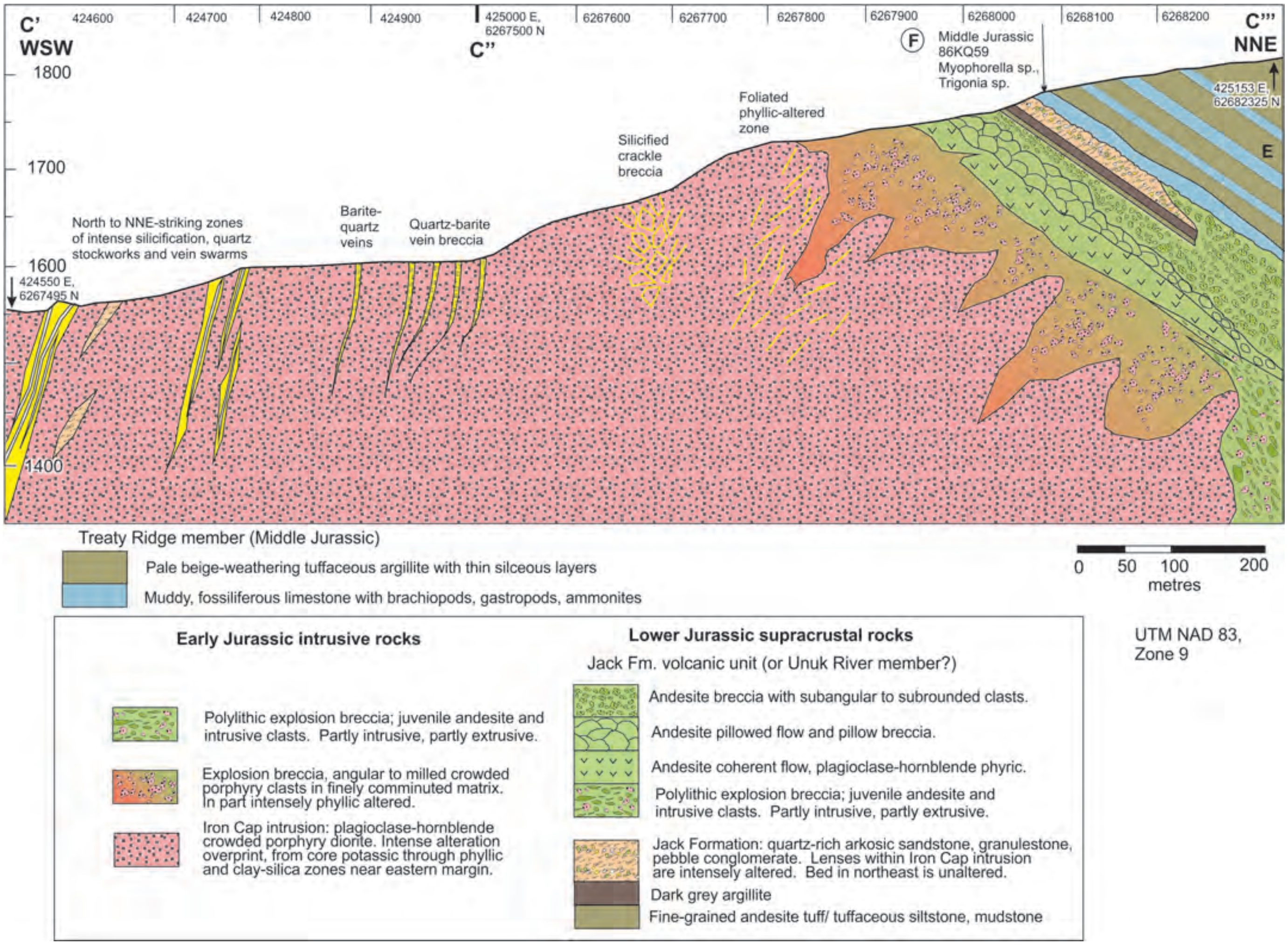


Fig. 17. Detailed eastern part of Iron Cap section.

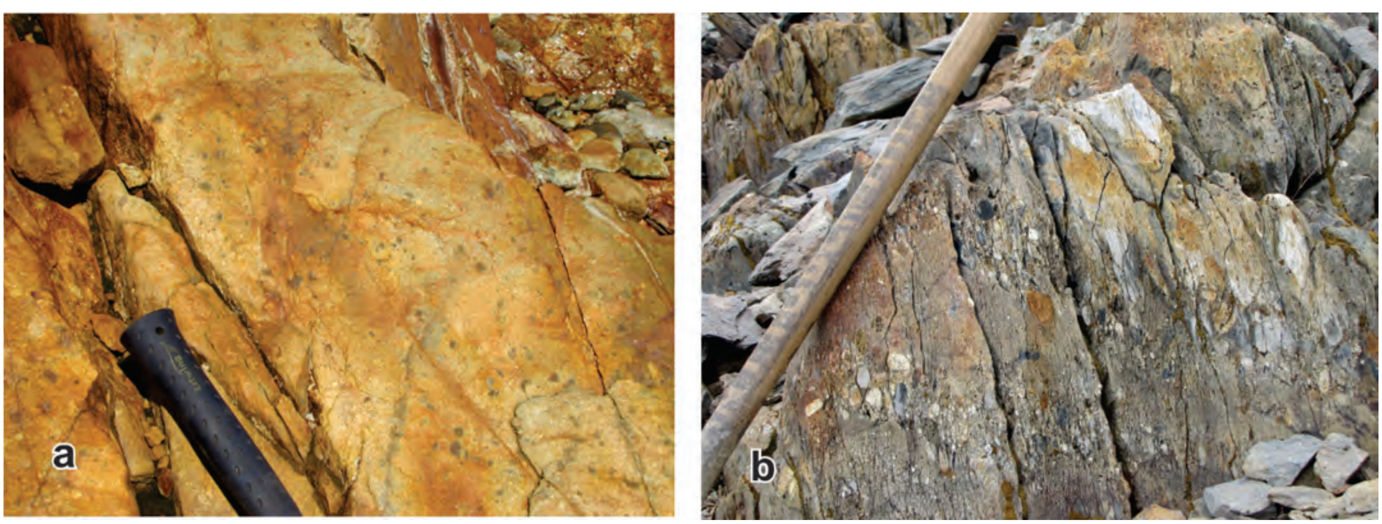


Fig. 18. Iron Cap photos. **a)** Jack Formation septa in the Iron Cap intrusion: highly altered polymictic pebble conglomerate with volcanic and quartz clasts, 424637 E, 6267358 N. **b)** Unaltered Jack Formation bed above the Iron Cap system: interbedded polymictic pebble conglomerate and pebbly sandstone with carbonaceous mudstone intraclasts, 425139 E, 6268056 N.

Fig. 19. Relationships between Jack Formation, porphyry intrusion, and phreatic explosion breccias in the Snowfield zone. **a)** Quartz-rich granulestone from inclusion within Snowfield zone intrusion (424699 E, 6264448 N; photo credit Gayle Febbo). **b)** Polymictic Jack Formation conglomerate from above western edge of Snowfield alteration zone (423837 E, 6263678 N). **c)** Unaltered explosive breccia with pink hypabyssal syenite clasts from west of the Snowfield zone. This breccia interfingers with and locally overlies Jack conglomerate of b); 423751 E, 6264170 N.

clast populations than the coarse conglomerates. In them, plagioclase porphyry, hypabyssal diorite and quartz stockwork clasts (Fig. 21b) probably reflect coeval sources related to the nearby Tennyson porphyry intrusion (~ 200 Ma, U-Pb, van Straaten, 2013) and its associated alteration zone. The quartz stockwork clasts are similar to those in breccia dikes in the Mitchell zone (see above). In the lower part of the section is a disaggregated hornblende-plagioclase phyric andesite flow with local peperitic textures, which is cut by clastic dikes. It probably was emplaced during conglomerate deposition.

The main exposure of conglomerate is separated by an east-vergent thrust fault from the Tennyson intrusion, which in turn is thrust eastward onto a sequence of monolithologic andesite conglomerates, breccias and volcaniclastic sedimentary beds (van Straaten, 2013) that probably belongs to the Unuk River member. The porphyry intrusion is affected by zones of potassic, phyllic and propylitic alteration; at one locale northerly quartz vein swarms were observed (428000 E, 6236450 N).

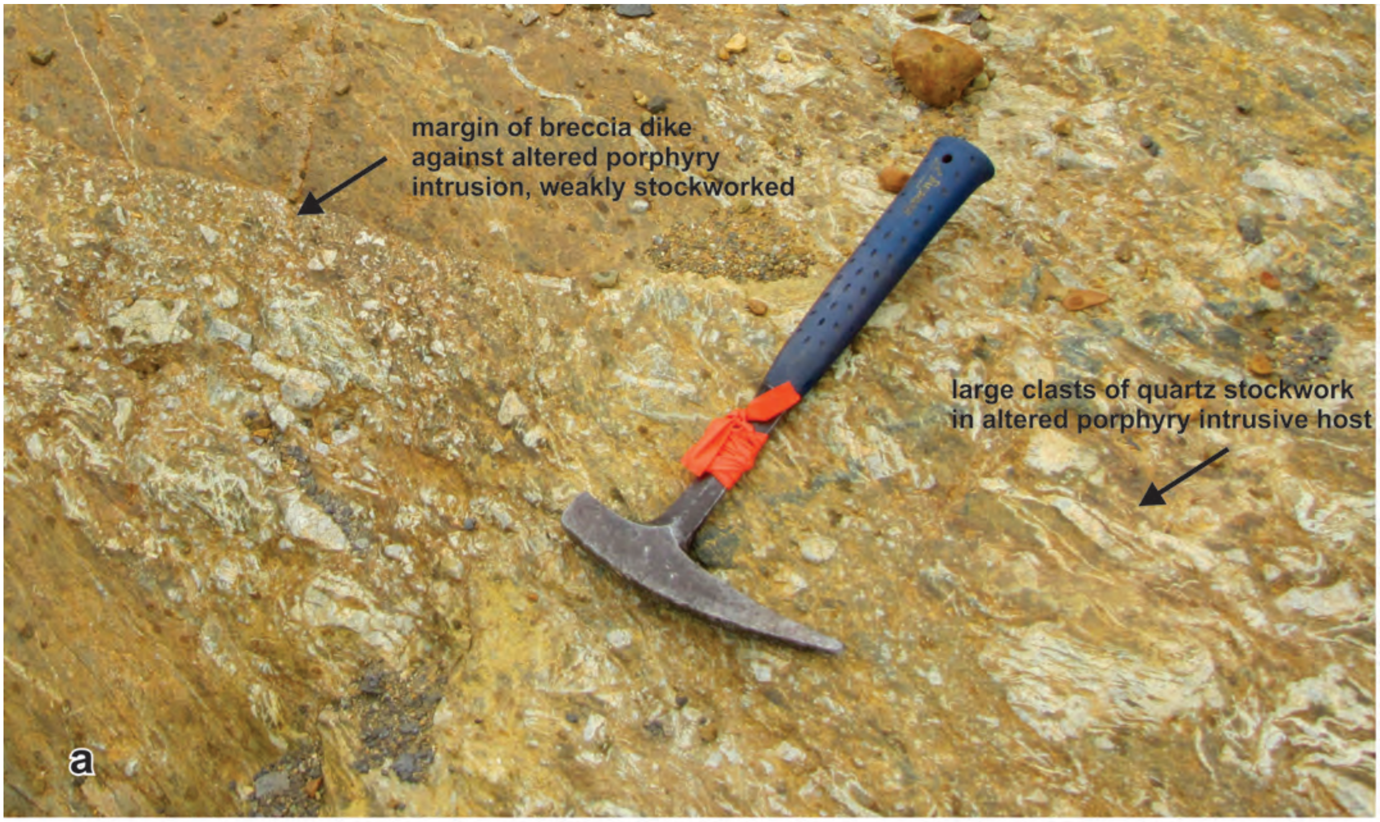
The thick, very coarse, poorly bedded and sorted, lithic-matrix conglomerate unit at Tennyson does not resemble the Jack Formation on the flanks of the McTagg anticlinorium. However, it is very similar to basal conglomerates of the Hazelton Group regionally, such as near the town of Iskut (Ash et al., 1997a) and in the Terrace area (Nelson et al., 2008).

6. Discussion

Because all Hazelton Group units thin markedly across the axis of the McTagg anticlinorium (Figs. 3, 4; see also Lewis, 2013) it probably was a paleohigh during the Early Jurassic. Stratigraphic and sedimentologic data presented above from the Jack Formation on the periphery of the McTagg anticlinorium are consistent with this interpretation and with syndepositional faulting during initial Hazelton Group sedimentation. Below we: 1) discuss lateral and vertical relationships of Jack Formation facies (Fig. 22) and present a first-order paleogeographic analysis; 2) evaluate the significance of detritus in the Jack Formation that is compositionally mature relative to subjacent source rocks and regional basal Hazelton Group units; 3) consider how structural and aeromagnetic data in the area contribute to the concept of syndepositional fault-controlled sedimentation, magmatism, and mineralization, and 4) present a regional model for Early and Middle Jurassic tectonism.

6.1.Variation of the Jack Formation near the McTagg anticlinorium

Although a paleosol is lacking at the Stuhini Group-Jack Formation unconformity, sharpstone conglomerates containing clasts derived from immediately subjacent Stuhini basement at the Treaty Glacier and Brucejack sections may represent mechanical weathering fronts developed on a gently sloping upland on the eastern flank of the McTagg anticlinorium. Similar basal sharpstone conglomerates are lacking west of the anticlinorium. Instead isolated remnants of carbonaceous mudstone (± fine-grained sandstone) are the lowest preserved rocks, and at the Bruce Glacier section, the basal Jack



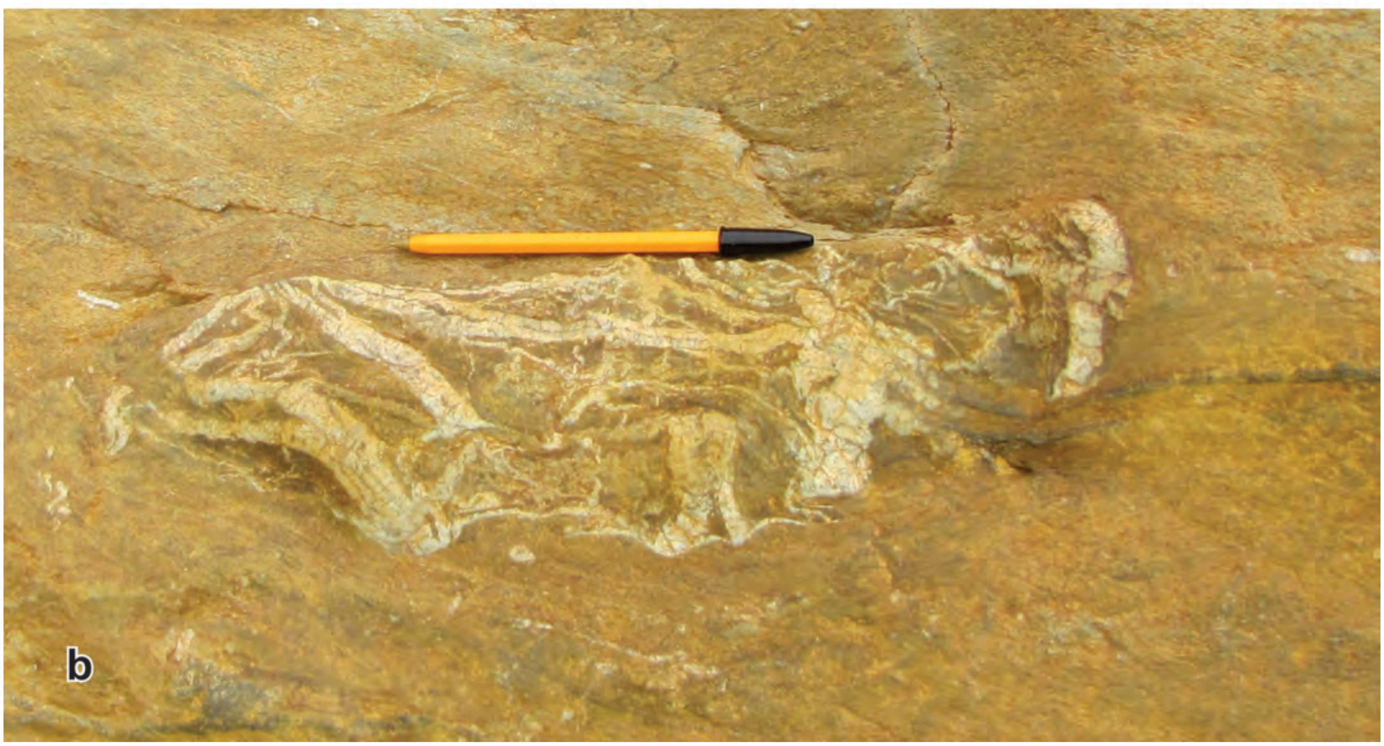


Fig. 20. Breccia dikes, Mitchell intrusion. **a)** Breccia dike of quartz stockwork clasts ("bone breccia") in the Mitchell intrusion (423467 E, 6265668 N). Stockworks cut relatively older phase of intrusion; dike emplaces fragmented stockwork into relatively younger phase. **b)** Detail of quartz stockwork clast in breccia. Note that veins lack a preferred orientation.

Formation consists of ~ 100 metres of polymictic cobble-boulder conglomerate with felsic extrusive and intrusive clasts. The mudstones at the base of the section imply abrupt basin deepening and underfilled conditions during initial

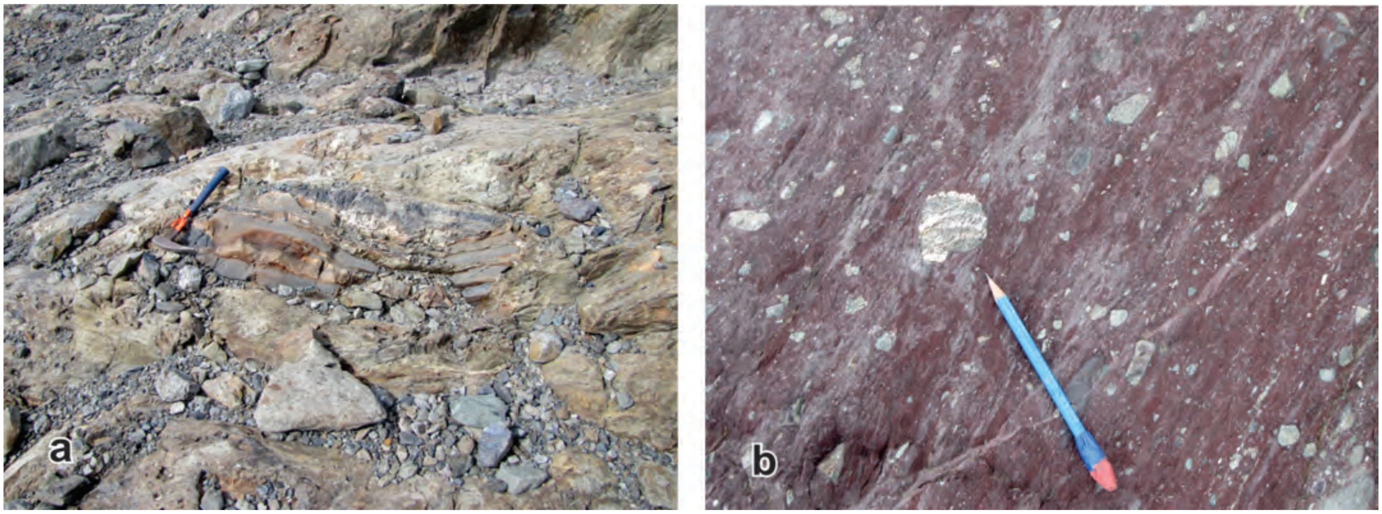


Fig. 21. Conglomerates at Tide-Tennyson. **a)** Coarse, poorly sorted conglomerate with mainly volcanic clasts. Large clast in centre of photo is limestone with bedding-parallel chert, probably derived from Permian limestone, 427213 E, 6236386 N; **b)** Pebbly mudstone with angular to subrounded hypabyssal porphyry and quartz clasts. Pencil points to quartz stockwork clast, 427193 E, 6236240 N.

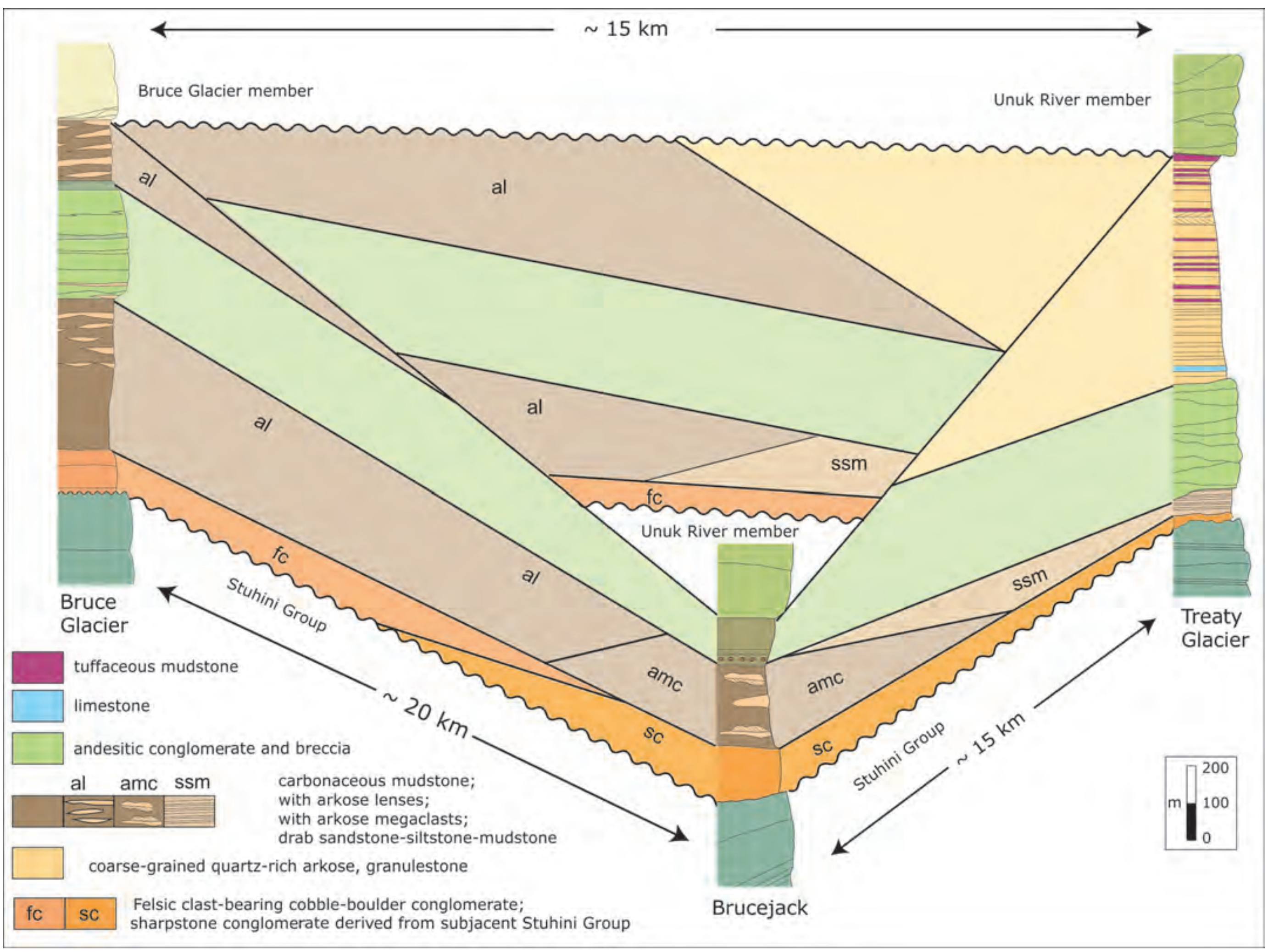


Fig. 22. Fence diagram illustrating facies relationships in the Jack Formation, McTagg anticlinorium.

sedimentation. The influx of polymictic conglomerates, which thicken and coarsen south of the Bruce Glacier section, implies uplifting, significant relief, and an integrated drainage system drawing from diverse, but proximal, sources.

At the Bruce Glacier section, the 400-m thick section of carbonaceous mudstone above the basal conglomerate represents a return to underfilled conditions and signifies abrupt, likely fault-induced, basin deepening. Sparse cross stratification in mass flow sandstone lenses indicate sediment sources to the east, from the region of now occupied by the McTagg anticlinorium. This facies thins east across the McTagg anticlinorium to 80 metres or less at the Treaty Glacier section and 200 metres at the Brucejack section (Fig. 22). Arkose megaclast-bearing olistostromes in carbonaceous mudstones at the Brucejack section attest to burial, lithification, uplift, and cannibalization of previously deposited Jack Formation, indicative of coeval faulting and fault-induced changes in basin morphology.

In the Bruce Glacier and Treaty Glacier sections, andesitic pyroclastic and epiclastic volcaniclastic rocks in the middle of the Jack Formation (Fig. 22) represent an episode of intense volcanism. Black mudstone intraclasts in the volcaniclastic units indicate that background deep-water sedimentation resumed during intervals of volcanic quiescence. The thick coarse volcaniclastic sections at the Bruce Glacier and Treaty Glacier sections suggest proximity to discrete coeval volcanic centres. The Iron Cap section and relationships at the Snowfield and Mitchell zones also record the development of Early Jurassic volcanic centres during deposition of the Jack Formation. Jack Formation siliciclastic units were host to the intrusions, as indicated by septa of likely basal Jack Formation in the intrusion, but were also deposited on their extrusive carapaces, where unaltered Jack conglomerates interfinger with plutonic clast-bearing explosive breccias (Figs. 16, 17). Surface eruption of phreatic explosive breccias composed of milled, high-level intrusive and quartz stockwork clasts could have provided hypabyssal and polycrystalline quartz detritus to the Jack Formation (see below).

At the Bruce Glacier section, the volcaniclastic facies grades back into a mudstone-rich siliciclastic section and a return to deep-water sedimentation interrupted by coarse-grained mass flow pulses. In marked contrast, at the Treaty Glacier section, rocks above the volcaniclastic facies indicate shallow-marine sedimentation (basal limestone beds with shelly fauna, sandstones with interference ripples and plant debris, polymodal paleocurrents). Apparently, as with the onset of Jack Formation sedimentation, the region on the northeastern side of the McTagg anticlinorium was high standing relative to the western side.

In summary, the Jack Formation provides important insights into events during earliest Hazelton deposition and emplacement of the Mitchell porphyries and their accompanying mineralization, including older episodes in the Brucejack system. Depositional patterns and overall thickness variations display evidence of syndepositional faulting and that the McTagg anticlinorium was probably a regional topographic high during sedimentation.

6.2. Compositional maturity of Jack Formation arenites and conglomerates

The Jack Formation is distinguished as a unit by polymictic conglomerates with felsic intrusive and extrusive clasts, and quartz-rich arkoses. Elsewhere throughout Stikinia, basal Hazelton Group units consist of mantle-derived volcanic rocks and compositionally immature sedimentary rocks, including thick, coarse basal conglomerates that in some cases contain olistostromal blocks (Greig, 1992, Ash et al., 1997a, Nelson et al., 2008). A local example is near the Tennyson prospect, where a 500 metre-thick very coarse basal conglomerate was derived from local fault block uplift of Stuhini Group and Stikine assemblage basement, as well as internally derived volcanic and explosive sources. Compared to these, and to underlying basement rocks, quartz grains and felsic volcanic and intermediate plutonic detritus are significantly over-represented in the Jack Formation. A similar mismatch between quartz-rich sedimentary rocks and subjacent greenstone belt sources has been noted in the Archean (Donaldson and Jackson, 1965; Condie, 1981). They argued that concentration of quartz from minor sources such as felsic volcanic and plutonic rocks and quartz veins requires extreme tropical weathering and/or multiple cycles of erosion and deposition. However, the paleolatitude of Early Jurassic Stikinia was ~ 32^{o} North (Kent and Irving, 2010), north of tropical latitudes, and Pleinsbachian ammonite faunas are a mixture of warm-water and cold-water species (Smith et al., 2001). Nonetheless, ferns and woody debris in the Jack Formation suggest moist, temperate conditions. Hence we suggest that the compositional maturity of the Jack Formation records both warm, wet chemical weathering and a protracted period of tectonic quiescence following the end-Stuhini deformational event. Regionally, the oldest known rocks in the Hazelton Group are ~ 203-205 Ma (Griffith Creek volcanics, Spatsizi area, Marsen and Thorkelsen 1992; basal Telkwa Formation, Terrace area, J. Nelson and R. Friedman, unpublished data 2013; basal Hazelton Group, Iskut area, Ash et al., 1997b). Fossil ages from the Jack Formation and oldest Jurassic igneous ages in the KSM area are Hettangian-Sinemurian, ~ 192-195 Ma (Table 1; Kirkham and Margolis, 1995). A protracted interval of uplift and erosion, perhaps as long as 10 million years, could have intervened in this area between the end of Stuhini deformation and the onset of Jack sedimentation. During this interval, the most mechanically durable and chemically stable minerals and rock types would have been preferentially preserved. Potential silica-rich sources include small (< 1 km^2), local intermediate intrusive bodies (see Lewis, 2013 for distribution) and Stuhini felsic volcanic rocks, such as those at Brucejack. Contributions from local coeval explosive eruptions could have enhanced the proportions of felsic and quartz vein material, as is seen from the incorporation of these clasts in near-surface breccia dikes and in phreatic explosion breccias at Iron Cap and the Bruce Glacier section.

6.3. Structural considerations

The eastern margin of the McTagg anticlinorium is a

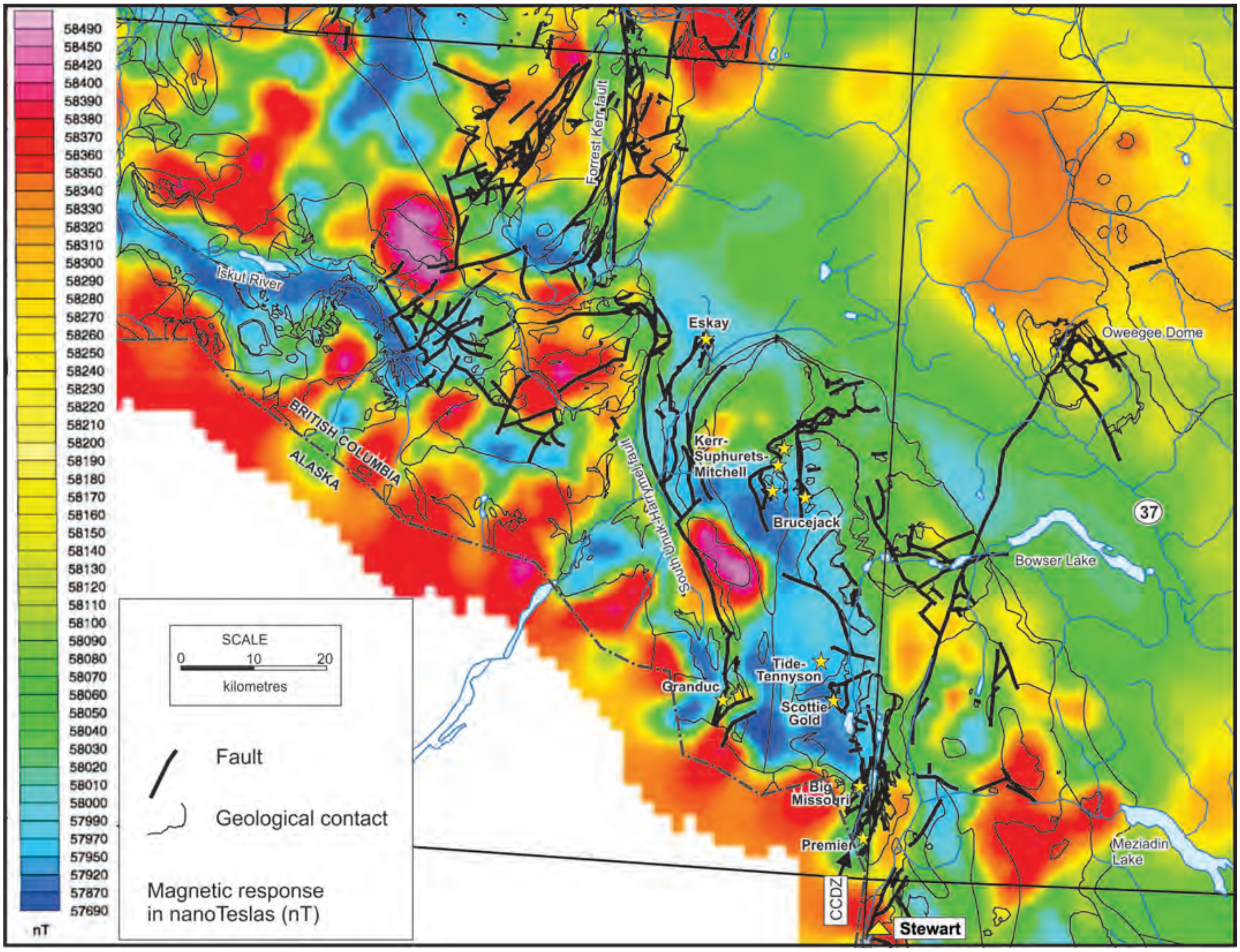


Fig. 23. Aeromagnetic map of the Treaty-Stewart trend and western Iskut region. Faults and contacts from the digital geological map of British Columbia 2005 from Massey et al. (2005).

likely location for an Early Jurassic basin-bounding fault, in that the Kerr-Sulphurets-Mitchell-Iron Cap system forms a continuous 12 kilometre-long zone of intrusion, alteration, and mineralization in the immediate footwall of the Sulphurets thrust fault at its eastern boundary. Veins and alteration zones trend either northerly parallel to the anticlinorium, or east-west at high angles to it (Kirkham and Margolis, 1995, their Fig. 2). Detailed geological mapping and extensive core logging at the Brucejack property have revealed a complex stratigraphy in the lower Hazelton Group, with rapid local facies changes probably controlled by penecontemporaneous faults (Pretivm Resources, 2012). Their model invokes a set of north-south and subsidiary east-west faults that were active during deposition, eruption, intrusion, and mineralization. The newly discovered Cleopatra vein in the Valley of the Kings zone trends north-northeast and is considered to be a feeder to the system (W. Board, personal communication, August 2013). On a broader scale, the prominent north-striking Brucejack fault (Fig. 4) trends through the Brucejack area for over 11 km between the Valley of the Kings zone on the east and the Snowfield and Golden Marmot zones on the west. It offsets upper Hazelton and Bowser Lake Group units (Lewis, 2013), and was active as late as Eocene (Kirkham and Margolis, 1995). However, its position within and parallel to the overall zone of alteration and mineralization suggest that it is a remobilized Early Jurassic structure (W. Board, personal communication, 2013).

A similar structural setting is likely for the Tennyson porphyry, adjacent to a Hazelton basin-margin fault, as shown by thick, coarse conglomerate in the fault panel immediately to the west. The intervening fault was subsequently remobilized as a Cretaceous east-vergent thrust.

On a regional scale, the northerly trends of mineralization reflect deep north-trending basement structures identified aeromagnetically (Fig. 23). A broad magnetic low is bounded to the west by the South Unuk-Harrymel fault, and to the east by the Cascade Creek deformation zone. Surface exposures in this broad, north-trending zone include the entire stratigraphic column of western Stikinia, units that range in age from Paleozoic to Eocene. Only the Eocene plutons stand out as isolated magnetic highs. The dimensions, uniformity and lack of

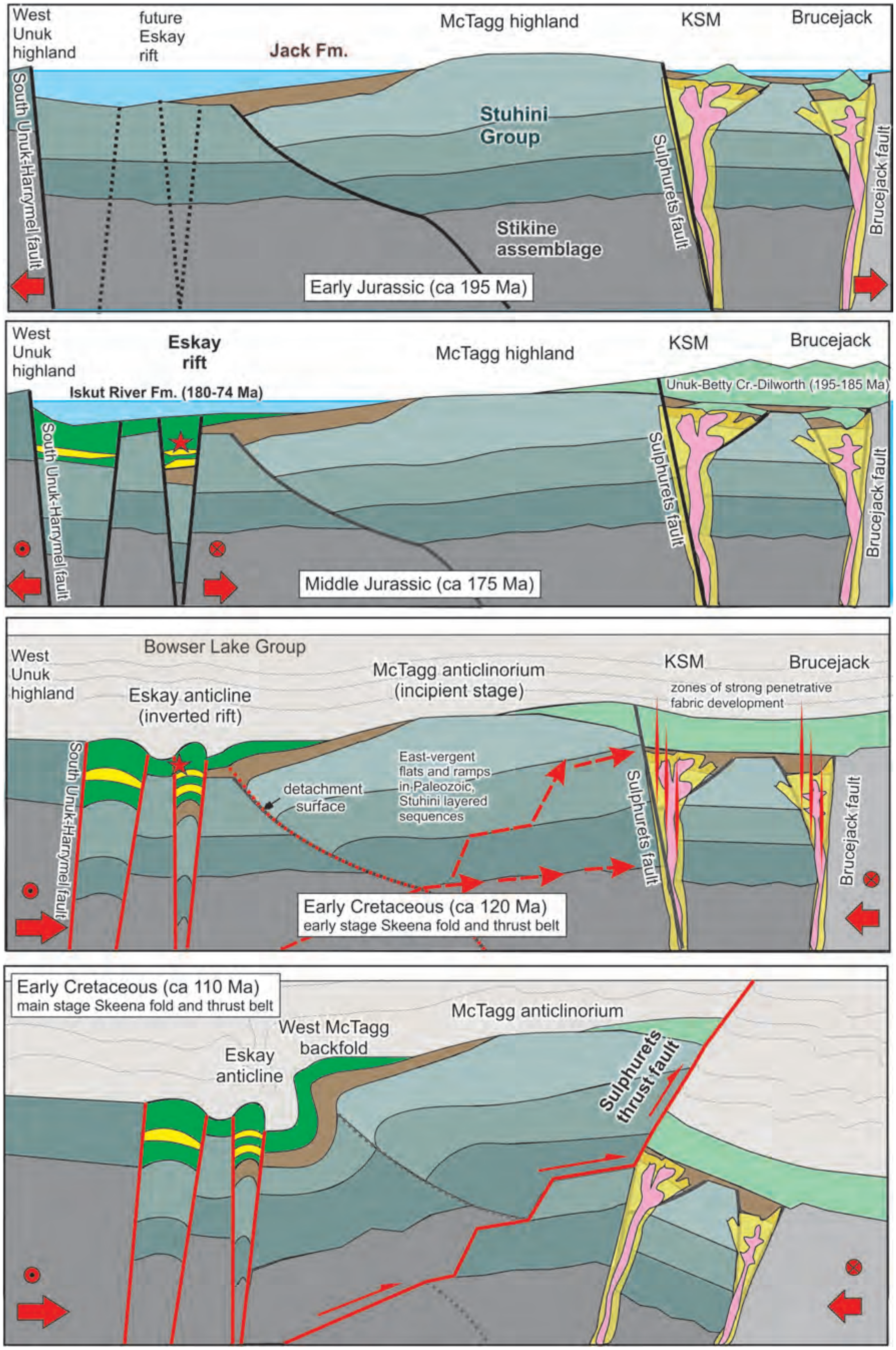


Fig. 24. Model for the structural evolution and reactivation of the McTagg half-graben and Eskay rift.

response to different supracrustal units argue for a deep crustal source, probably related to magnetite destruction by regional-scale alteration. The most likely time frame for this event would be during the Early Jurassic, as a broader expression of the fluid flow systems that produced intense local alteration around the porphyry and related deposits. The framing of this crustal-scale alteration system by the South Unuk-Harrymel fault and Cascade Creek deformation zone implicates them as block-bounding features in Early Jurassic time.

6.4. Early and Middle Jurassic tectonic reconstructions

The east-vergent Cretaceous Skeena fold and thrust belt structures that are prevalent throughout the region can be modelled as reactivated Jurassic basin-bounding faults. Figure 24 shows Early and Middle Jurassic tectonic reconstructions along a NW-SE cross section through Eskay Creek, the McTagg anticlinorium, and the KSM-Brucejack area. The Eskay Creek deposit is in a narrow, north-northeast trending sub-basin of the Middle Jurassic Eskay rift (Alldrick et al., 2005), which has since been inverted to form the Eskay anticline (Fig. 24). Pop-up structures like this are a common feature of basin inversion, as shown by McClay et al. (1989) in their analysis of Jura-Cretaceous northeast-vergent compression superimposed on rift basins of the Paleozoic Kechika trough of northeastern British Columbia. In contrast, the Sulphurets thrust fault that forms the eastern boundary of the McTagg anticlinorium is modelled as a reactivated but not inverted structure. It is comparable to the Mt. Waldemar fault in the Kechika trough; both were originally steep normal faults on the west side of graben that became ramps in subsequent east-vergent thrusting. As the proto-Mt. Waldemar fault formed the plumbing system for Devonian sedex deposits (McClay et al., 1989), so the proto-Sulphurets fault may have been the conduit for the Kerr-Sulphurets-Mitchell-Iron Cap porphyries and associated hydrothermal fluids. The precursor of the McTagg anticlinorium is the McTagg highland, a Jurassic topographic high that supplied sediments to adjacent depocentres, underlain by a west-tilted half graben. This reconstruction explains the thinning of all Hazelton units across the anticlinorium, and the contrast between the Eskay rift to the west, with its thick Iskut River Formation bimodal volcanic and sedimentary fill, and very thick lower Hazelton accumulations to the east overlain by thin, rift-shoulder Middle Jurassic units. It also accounts for the sedimentologic contrast between the deep Jack basin on its western flank, with coarse conglomerates that probably were fed by an extensive drainage system, and smaller-scale, more structurally complex depocentres to the east that hosted volcanic and porphyry centres.

The relative importance of orthogonal extension versus transtension in driving basin subsidence is unclear. The only demonstrable Jurassic sinistral motion in the region is shown by the ~ 172 Ma synkinematic dike in the south Unuk fault zone on the western margin of the Eskay rift (Lewis et al., 2001). Indicators of sinistral shear are well developed, but generally attributed to the Skeena fold and thrust belt (Kirkham and Margolis, 1995). The teardrop shape of the McTagg anticlinorium, with its highly attenuated southern "tail", is consistent with a positive flower structure. Preliminary field observations in the tail area in 2013 indicate very strong sinistral shear sense in andesitic and felsic tuffs. Samples are being processed to determine protolith ages.

7. Conclusions and future directions

Facies analysis of the Jack Formation is in agreement with regional evidence that first-order structures of the Cretaceous Skeena fold and thrust belt, from the Eskay anticline to Stewart, are reactivated Jurassic (and possibly older) faults that controlled intrusion, alteration and mineralization. The overall northerly trend of Early Jurassic mineralization coincides with a set of original basin-bounding faults, that developed during extensional or transtensional tectonics that prevailed during development of the Hazelton arc. U-Pb analysis of detrital zircons is in progress to identify sources of the Jack Formation. Future work will focus on additional sections of the Jack Formation and structural mapping of the mineralized corridor between Brucejack and Stewart.

Acknowledgments

This project was conceived through the innovation and enthusiasm of Adrian Hickin. Larry Diakow aided greatly in project design, bringing to bear his deep knowledge of the Hazelton Group. Warwick Board and Charlie Greig of Pretivm Resources and Mike Savell and Gayle Febbo of Seabridge Resources generously shared their observations and ideas. Larry Aspler contributed key sedimentological insights and commented on an early draft of the manuscript. Tian Han and Lauren Wilson were sturdy companions in the field and made important contributions such as multispectral analysis of alteration zones (TH) and digital compilations (LW). We thank Prism Helicopters base manager Lewis Tuck and his crew for excellent, safe service in sometimes difficult flying conditions.

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