Did epithermal mineralization in the northern Toodoggone region develop synchronously with large-scale folding?

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Abstract

In the eastern part of central Stikinia, regional northwest-plunging, northeast-vergent folds are indicated by stratigraphic relationships. A synclinorium southeast of Sustut Provincial Park is connected to an anticlinorium in the northern Toodoggone region by a long (ca. 100 km) southwest-younging limb. The hinge zone of this anticlinorium coincides with the Black Lake intrusion (Early Jurassic), which cuts volcano-sedimentary rocks that host epithermal Au-Ag±Cu mineralization (e.g., Baker, Lawyers, Shasta deposits). Although intrusion-related porphyry mineralization is common along the length of eastern Stikinia, northern Toodoggone epithermal mineralization, which is distributed along the axial trace of the anticlinorium, appears to be unique. This geometric and apparent temporal coincidence may imply a causal relationship between folding, intrusion, and epithermal mineralization. This hypothesis can be tested with high-precision geochronology.

Keywords: Toodoggone, epithermal Au-Ag±Cu, deformation, stratigraphic younging, Black Lake intrusion

1. Introduction

The Stikine terrane (Stikinia, Late Triassic to Jurassic) of the Cordilleran orogen (Fig. 1) hosts porphyry Cu-Au, epithermal Au-Ag±Cu, and volcanogenic massive sulphide deposits. In eastern Stikinia (Fig. 2), the Toodoggone region hosts one past-producing porphyry Cu-Au deposit (Kemess) and several epithermal Au-Ag deposits (e.g., Baker, Lawyers, Shasta). Diakow (2001) and Diakow et al. (1993, 2006) mapped the bedrock geology of the Toodoggone region, providing a geological framework for the mineral deposits, and Duuring et al. (2009) summarized the age of the host rocks and the timing and thermochemical conditions of mineralization. They showed that the Kemess porphyry mineralization (ca. 200 Ma) in the southern Toodoggone region is slightly older than the epithermal mineralization (<194 Ma) to the north. However, whereas mineralization-host rock relationships are well-established in the northern Toodoggone region, a large-scale structural control may have gone unrecognized.

A field reconnaissance of the northern Toodoggone area, on the traditional lands of the Tsay Keh Dene, Kwadacha, Takla Lake, Kaska Dena, and Tahltan First Nations, combined with published studies in the area (Diakow et al., 1993, 2001) and in the rest of eastern Stikinia (Lord, 1948; Richards, 1976; Diakow, 2001; Legun, 2001; Evenchick et al., 2007; Ootes et al., 2020a, b, 2022), allow regional tracing of stratigraphic younging directions. These define a northwest-plunging, northeast-vergent synclinorium-anticlinorium pair. A synclinorium southeast of Sustut Provincial Park in the south connects to an anticlinorium in the northern Toodoggone region by a long (ca. 100 km) intervening limb (Fig. 3). Coincident with the hinge zone of the anticlinorium is the Black Lake intrusive

Fig. 1. Terrane map of the Cordilleran orogen and location of this study (eastern Stikinia). Modified after Colpron (2020).

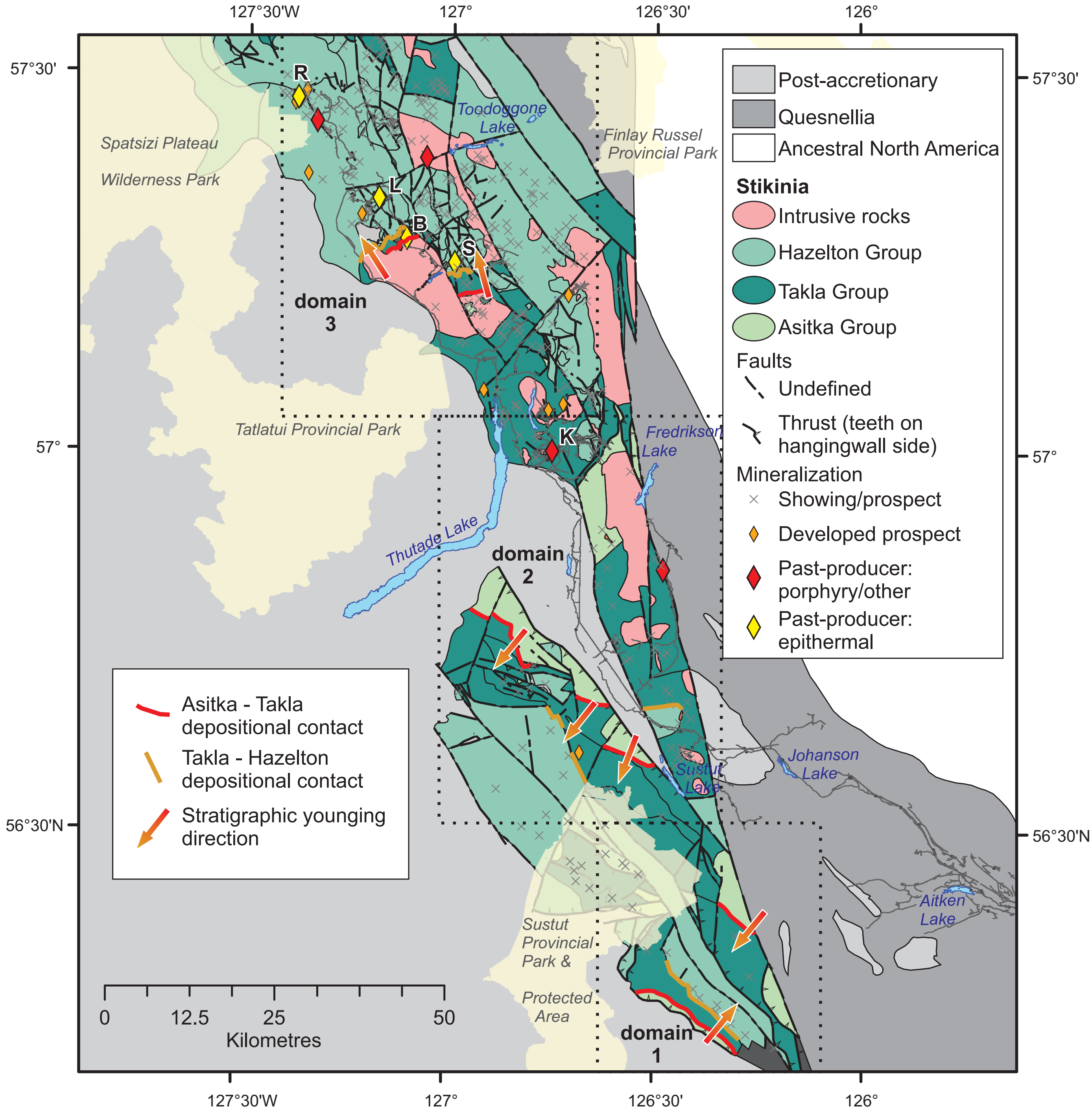

Fig. 2. Geology of eastern Stikinia, modified after Lord (1948), Richards (1976), Diakow et al. (1993, 2006), Diakow (2001), Legun (2001), Evenchick et al. (2007), and Ootes et al. (2020a). B-Baker mine; L-Lawyers mine; K-Kemess mine; R-Ranch project (Thesis mine); S-Shasta mine. Informal structural domains 1, 2, 3.

suite, and coincident with the axial trace of the anticlinorium is epithermal mineralization. Although porphyry mineralization is common in the eastern part of central Stikinia, epithermal mineralization is only known in the northern Toodoggone area. Geometric and possible temporal coincidence may indicate a causal link between folding, intrusion, and epithermal mineralization.

2. Eastern Stikinia

2.1. Stratigraphic framework

Although eastern Stikinia is dismembered by faults, which range from syndepositional and/or volcanic structures to Eocene and younger crustal-scale terrane-bounding structures (Richards, 1976; Diakow et al., 1993, 2006; Diakow, 2001; Legun, 2001; Evenchick et al., 2007; Ootes et al., 2020a),

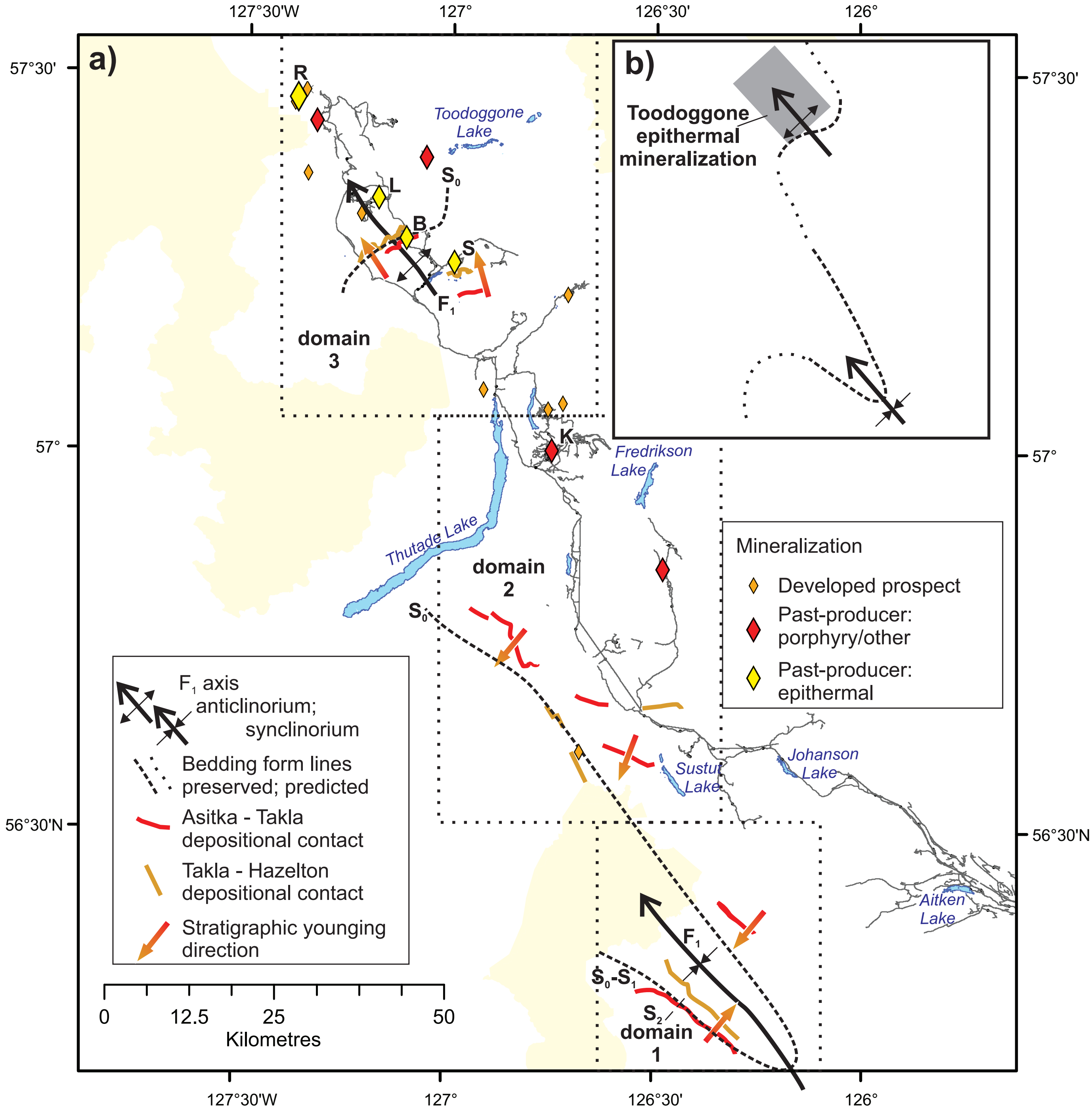

Fig. 3. a) Simplified geology from Figure 2 highlighting stratigraphic younging directions with a synclinorium in domain 1 and an anticlinorium in domain 3 (northern Toodoggone area) that are linked by a long southwest-younging limb (domain 2). Stratigraphic younging and structural interpretations in domain 1 are from Ootes et al. (2020a, b), in domain 2 from Richards (1976), Diakow (2001), and Legun (2001), and domain 3 from Diakow et al. (1993, 2006) and this study. B-Baker mine; L-Lawyers mine; K-Kemess mine; R-Ranch project (Thesis mine); S-Shasta mine. **b)** Sketch of fold relationships in eastern Stikinia based on stratigraphic younging directions in 3a, and highlighting the coincidence of the anticlinorium in domain 3 with epithermal Au-Ag±Cu mineralization.

unconformities can be used as form lines to define regional stratigraphic younging (Fig. 2). Eastern Stikinia is underlain by the Asitka Group (Carboniferous-Permian; equivalent to the Stikine assemblage in western Stikinia), the Takla Group (Upper Triassic; equivalent to the Stuhini and Lewes River Group in western and northern Stikinia), the Hazelton Group (Lower Jurassic), and felsic to mafic intrusions (Late Triassic to Early Jurassic; Fig. 2; Table 1). The eastern exposures of Stikinia are in fault contact with the Quesnel and Cache Creek terranes; to the west, Stikinia is overlain by the Bowser Lake

Table 1. Supracrustal units of eastern Stikinia. See Figures 2-3 for informal structural domains.

Supracrustal stratigraphy of eastern Stikinia

Structural domain	Group*	Formation	Stratigraphic age	Stratigraphic age (Stage)	Numerical age Circa (Ma)	Description	Source
3 (northern Toodoggone)	Hazelton	Toodoggone	Lower Jurassic	Sinemurian	198 to 192	felsic-intermediate flows and felsic tuff, conglomerate	*3*
	Takla	-	Upper Triassic	-	-	mafic volcanic and related sandstone and siltstone	*3*
	Asitka	-	Late Carboniferous to Lower Permian	-	-	limestone, chert, tuff	*3*
2 (southeast of Kemess mine area)	Hazelton	Toodoggone	Lower Jurassic	Hettangian to Sinemurian	201 to 190	felsic-intermediate flows and epiclastic sandstone and conglomerate	*4*
	Takla	-	Upper Triassic		-	mafic volcanic and related sandstone and conglomerate, local mudstone	*2, 4*
	Asitka	-	Middle Pennsylvanian	Moscovian	309	chert, limestone, mafic and intermediate flows, felsic tuff	*4*
2 (northeast of Sustut Provincial Park)	Hazelton	Telkwa	Lower Jurassic	Sinemurian	-	mudstone, epiclastic sandstone and conglomerate	*1, 5*
	Takla	Moosevale	Norian	Norian	-	mafic-intermediate sandstone, conglomerate, breccia	*2, 5*
	Takla	Savage Mountain	Carnian	Carnian	-	mafic volcanic breccia and pillow lava	*2, 5*
	Takla	Dewar	Carnian	Carnian	-	siltstone, mafic sandstone and conglomerate	*2, 5*
	Asitka	-	Permian (Cisuralian)	-	-	chert, tuff, shale, volcanic, and carbonate	*2, 5*
1 (southeast o Sustut Provincial Park)	Hazelton	Telkwa	Lower Jurassic	Sinemurian	196	mudstone, epiclastic sandstone and conglomerate	*1, 6*
	Takla	±Savage Mountain	Upper Triassic	Carnian		mafic volcanic breccia and pillow lava	*2*
	Takla	Dewar	Upper Triassic	Carnian		siltstone, mafic sandstone and conglomerate	*2, 6*
	Asitka Group		Permian (Cisuralian)	Asselian-Sakmarian	290	phyllite, chert, intermediate and felsic volcanic	*6*

*Takla Group is considered equivalent to Stuhini and Lewes River groups in other parts of Stikinia
Thick black lines between groups represent unconformities
1 - Tipper and Richards, 1976
2 - Monger and Church, 1977; Monger, 1977
3 - Diakow et al., 1993, 2006
4 - Diakow, 2001
5 - Legun, 2001
6 - Ootes et al., 2022

and Sustut groups (Late Jurassic to Cretaceous; Figs. 1 and 2; Lord, 1948; Monger and Church, 1977; Richards, 1976; Tipper and Richards, 1976; Monger, 1977; Diakow, 2001; Diakow et al., 1993, 2006; Legun, 2001a; Evenchick et al., 2007; Ootes et al., 2020a, b, 2022).

In structural domain 1 southeast of Sustut Provincial Park (Fig. 2; Table 1), the Asitka Group is mostly deep-water mudstones (now phyllites) with lesser chert and minor volcanic rocks that are unconformably overlain by thick bedded mafic clast-bearing sandstones, interbedded argillite, and lesser cobble conglomerates of the Dewar Formation (Takla Group). In that area, rocks of the Dewar Formation are in direct contact with unconformably overlying phyllitic mudstones and epiclastic conglomerates of the Telkwa Formation (Hazelton Group; Ootes et al., 2020a, b; 2022). To the north, in structural domain 2 east of Thutade Lake, intervening Takla Group units (Moosevale and Savage Mountain formations) are variably preserved and overlain by undivided Hazelton Group rocks (Fig. 2; Table 1; Richards, 1976; Diakow, 2001; Legun, 2001). In structural domain 3 in the Toodoggone area (Fig. 2; Table 1), the Asitka Group is predominantly platformal fossiliferous carbonate rocks that are overlain by pyritic siltstones and massive mafic volcanic rocks of the Takla Group. At the base of the Toodoggone Formation is a locally preserved unit of polymitic conglomerate and interbedded sandstone, a few metres thick, that is overlain by massive intermediate volcanic flows and tuffaceous rocks of the Toodoggone Formation (Hazelton Group) and its members (Diakow et al., 1993; 2006). In summary, the Asitka-Takla and Takla-Hazelton depositional contacts are unconformities.

2.2. Structural framework

Regional younging directions, from domain 1 in the south to domain 3 in the north, appear to preserve a northwest-striking and plunging, northeast-vergent synclinorium-anticlinorium pair linked through domain 2 by a long (ca. 100 km) northwest-striking, southwest-younging limb (Figs. 2, 3). The dashed lines on Figure 3b are idealized bedding formlines defined by unconformities; the dotted lines are predictions of where the formlines may have continued, but are not readily apparent due to structural dismemberment or from being hidden by overlying stratigraphic units. Notably, the epithermal Au-Ag±Cu mineralization in the northwestern Toodoggone area appears to fall along the axial surface trace of the domain 3 anticlinorium (Figs. 2, 3).

2.2.1. Structural domain 1

Large-scale younging defines a synclinorium in structural domain 1, southeast of Sustut Provincial Park (Figs. 2, 3). In the southwestern part, rocks young to the northeast, from lowermost Asitka Group, Takla Group (Dewar Formation), and Hazelton Group (Telkwa Formation; Fig. 2). In the northeastern part, units young to the southwest, from the Asitka Group to the Takla Group; the Takla-Hazelton group contact is interpreted as a thrust fault in this area (Fig. 2). The Asitka Group contains a strong first-generation foliation (S_1) that is parallel to compositional layering, with bedding in less competent layers transposed into the foliation. The Takla and Hazelton groups also contain this S_1 fabric although it is less strongly developed and bedding is better preserved (Ootes et al., 2020b). The S_1 parallels the unconformities as well as the predicted fold axis for domain 1, implying that the synclinorium is a first-generation fold (F_1; Fig. 3). The opposite stratigraphic younging directions and the axial planar S_1 indicate that domain 1 records a northwest striking and plunging F_1 synclinorium (Figs. 2, 3). In the same area, a northeast-striking second-generation foliation (S_2) is nearly perpendicular to and kinks the S_0-S_1 (Ootes et al., 2020b). It is likely that this S_2 fabric is related to the Cretaceous Skeena fold belt (e.g., Evenchick, 2001).

2.2.2. Structural domain 2

Structural domain 2 was not directly investigated in the current reconnaissance and geological contacts and structural measurements were extracted from mapping by Richards (1976), Diakow (2001), and Legun (2001). From the eastern side of the domain 1 north to Thutade Lake, folds are common in each stratigraphic unit but, overall, the stratigraphy youngs to the southwest (Fig. 2). Stratigraphic units include the Asitka Group, Takla Group (Dewar Formation and subdivisions of the Moosevale and Savage Mountain formations), and the Hazelton Group (subdivisions of the Telkwa Formation; Table 1). Farther north, east, and south of the Kemess mine area, Asitka Group and Takla Group are only preserved in structural contact (Diakow, 2001; Legun, 2001).

2.2.3. Structural domain 3 (northern Toodoggone region)

Between domains 2 and 3, stratigraphic contacts of major supracrustal units are not exposed. However, in domain 3 near the Lawyers, Baker, and Shasta mines in the northwestern Toodoggone area, the stratigraphic sequence is well-preserved, younging to the north-northwest, from Asitka Group to Stuhini Group to Hazelton Group (Figs. 2-4). The base of the lowest preserved Asitka Group stratigraphic unit is intruded by the Black Lake intrusive suite (Early Jurassic, 200 to 190 Ma; Fig. 4; Diakow et al., 1993, 2006; Bouzari et al., 2019). The Stuhini Group overlies the Asitka Group and is predominantly tan-rust-weathering pyritic siltstone that is ubiquitous throughout the Toodoggone region. Locally preserved basalts with pyroxene phenocrysts provide diagnostic evidence of the Takla Group (Monger, 1977; Monger and Church, 1977; Diakow et al., 1993). Stratigraphically above this is the Hazelton Group (Fig. 4), which is mostly felsic-intermediate flows and felsic tuffs of the Toodoggone Formation (Diakow et al., 1993, 2006). Unlike the domain 1 area to the south, penetrative deformation fabrics are rare.

3. Epithermal mineralization and relationship to folds in the northern Toodoggone region

The northern Toodoggone area (domain 3) contains past-producing epithermal Au-Ag±Cu mineralization (e.g., Shasta,

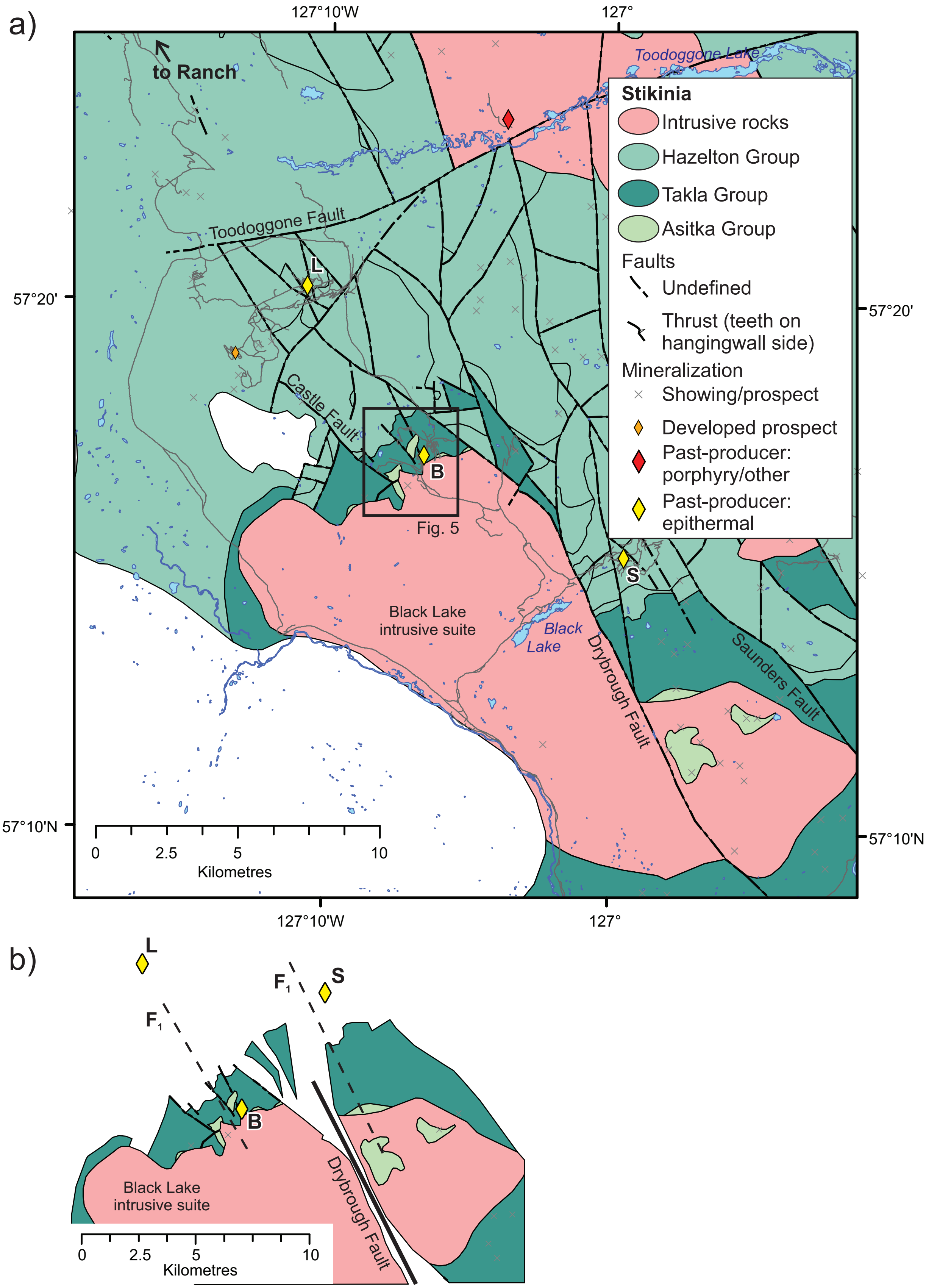

Fig. 4. a) Geology of the northern Toodoggone region, simplified after Diakow et al. (1993, 2006). B-Baker mine; L-Lawyers mine; S-Shasta mine. **b)** Simplified reconstruction across the Drybrough fault, showing potential locations of epithermal mineralization before dextral faulting.

Baker, Lawyers) and a number of advanced prospects and showings (Figs. 2, 3). The Baker deposit is hosted in the Asitka and Takla groups close to the contact of the Black Lake intrusive suite, which roughly parallels the overall supracrustal contacts (Figs. 4, 5). The Baker deposit is considered intermediate-sulphidation and has high-fluid temperature (>300°C) and salinity characteristics that are consistent with a genetic link to an underlying magmatic system (Duuring et al., 2009; Bouzari et al., 2019). The Shasta and Lawyers deposits are more distal from the intrusions and hosted in the Toodoggone Formation (Hazelton Group; Fig. 4). The Baker and Shasta mines are separated by the Drybrough fault (dextral); reconstructing units along the fault indicates that the Shasta and Lawyers deposits may have formed in similar stratigraphic and structural positions (Fig. 4b). The mineralization at Shasta and Lawyers is considered low-sulphidation, with low mineralization temperatures (ca. 200°C) and salinities that are most consistent with meteoric or metamorphic fluids (Duuring et al., 2009), possibly a reflection of distance from the Black Lake suite intrusive contact (Fig. 4b).

More detailed aspects of the domain 3 anticlinorium described above are preserved in the Baker mine area where northwest plunging folds are exposed (Fig. 5). Southwest of the mine site, bedding in the Asitka Group strikes southeast and dips west (160°/50°). Adjacent to the mine site, bedding strikes northwest and dips east (340°/45°). East of the mine site, bedding strikes west and dips north (260°/70°). The unconformity with the overlying Takla Group parallels bedding. The Black Lake suite intrusive contact is only preserved in Asitka Group outcrops in the southwest and east on Figure 5, and its trace under surficial cover is speculated (Fig. 5a). In general, the Takla-Hazelton group unconformity parallels Asitka-Takla group relationships (Figs. 2, 3, 4a).

Epithermal mineralization in domain 3 is distributed along the axial trace of the regional anticlinorium (Fig. 3) and in the hinge zone, perpendicular to stratigraphic and intrusive contacts (Fig. 4b). Zones of extension related to folding mechanisms are well-understood (e.g., Cosgrove, 2015), and this hinge location is consistent with zones of dilation and fluid flow for mineralization. This geometry suggests a twofold causal relationship. First, positioned in the hinge zone of the anticlinorium, the Black Lake intrusion may have been emplaced during folding using volume created by extension in the outer arc of the fold. Second, hydrothermal fluids generated by magma exsolution may have migrated into overlying supracrustal units along similar shallow-level space-accommodating brittle faults, precipitating Au-Ag±Cu epithermal mineralization at high crustal levels, both in the hinge zone and downplunge along the axial trace. Tied to a unique structure, this hypothesis would explain why epithermal mineralization appears to be unique to the northern Toodoggone area and lacking elsewhere in in eastern Stikinia (Figs. 2, 3).

4. A test: Timing of deformation and mineralization

If the relationships between deformation and mineralization presented above are correct, they should coincide with the crystallization age of at least one phase of the Black Lake intrusive suite. South of the epithermal mineralization, near the Kemess mine (Figs. 2, 3), different intrusive suites and sub-phases are recognized and dated. For example, the phase that hosts the Kemess porphyry deposit is dated at ca. 200 Ma (U-Pb zircon; Re-Os molybdenite; Diakow, 2001; Duuring et al., 2009). In the Baker epithermal mineralization area (Fig. 4), molybdenite in a quartz-feldspar porphyry has yielded a 194 ±0.8 Ma Re-Os date (Bouzari et al., 2019). Individual intrusive phases of the Black Lake suite have not been separated and the U-Pb zircon ages that have been reported (Diakow et al., 1993; Bouzari et al., 2019) are too imprecise to resolve the relationships between intrusive phases and mineralization. North of the Baker mine and immediately above the Takla Group, Toodoggone Formation volcanic rocks yielded an Ar-Ar age of 194.2 ±0.4 Ma (Diakow et al., 2006), which improved upon a previously reported 193 ±2.7 Ma age (K-Ar) from the same location (Diakow et al., 1993). A statistically indistinguishable Ar-Ar age determination of 193.8 ±2.6 Ma was reported from the Shasta mine area, but was interpreted as a cooling age of the alteration assemblage associated with epithermal mineralization (Diakow et al., 2006). In general, ca. 200 to ca. 185 Ma Ar-Ar and lesser U-Pb zircon volcanic crystallization age determinations are consistent throughout the Toodoggone Formation (Diakow, 2001; Diakow et al., 2006; Duuring et al., 2009). The Lawyers epithermal deposit is hosted in a volcanic unit that is stratigraphically above the Toodoggone Formation flow dated at ca. 194 Ma, thus mineralization at Lawyers has to be younger than ca. 194 Ma.

Duuring et al. (2009) compiled available age data from the entire Toodoggone region and showed that the epithermal mineralization at Lawyers and Shasta may be younger than the Baker mineralization. However, some of the age determinations in that compilation were from outdated techniques (e.g., K-Ar) and the accuracy and precision of these determinations are difficult to assess. Bouzari et al. (2019) presented U-Pb zircon results derived from LA-ICP-MS (laser ablation inductively coupled plasma-mass spectrometry); the reported uncertainties (~±2 Ma) are significant underestimates because they are derived from weighted means of single zircons with >20 million year ranges, with individual uncertainties ±10 Ma (2σ). These results are far less precise than U-Pb zircon dating by CA-IDTIMS (chemical abrasion isotope dilution thermal ionization mass spectrometry) that routinely generate dates with uncertainty less than 0.5 Ma (2σ).

The critical chronological test now rests with new modern U-Pb zircon dates (CA-IDTIMS) from the intrusive phases of the Black Lake suite and Ar-Ar laser step-heating dates from alteration mineral assemblages associated with epithermal mineralization at Baker, Lawyers, Shasta, and other deposits in the area. Because mineralization at Lawyers and Shasta appears to have been deposited from relatively low-temperature fluids (ca. 200°C; Duuring et al., 2009) and because Ar-Ar laser step-heating dating is only appropriate for higher

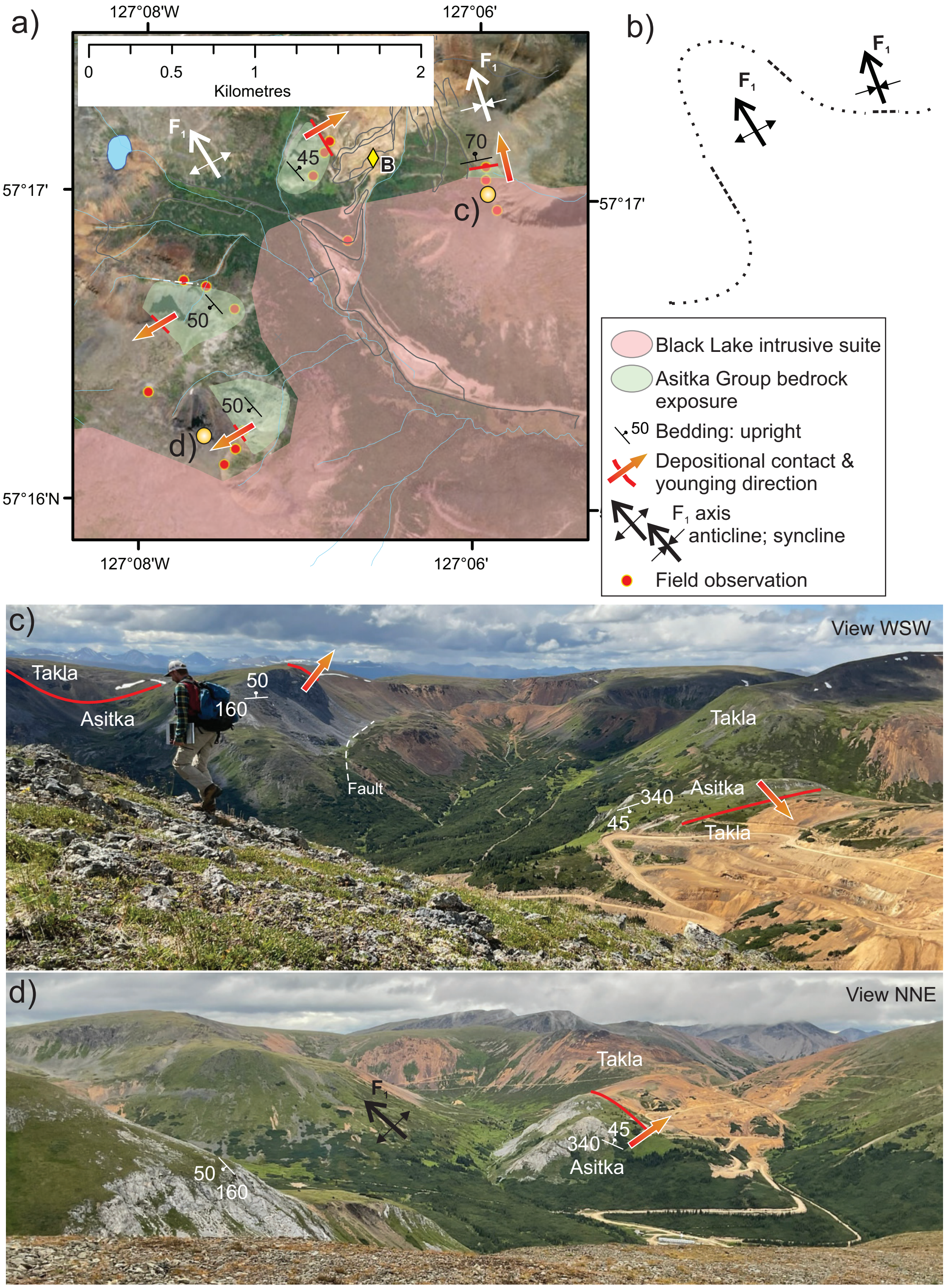

Fig. 5. Folds in the northern Toodoggone area from observations near Baker mine (see Fig. 4 for location). **a)** Geology near Baker mine (B) showing Asitka Group outcrops, bedding orientations, and contacts with overlying Takla Group and younging directions. Yellow dots refer to the photograph location in c) and d). **b)** Sketch of fold relationships in the Baker mine area based on bedding in the Asitka Group and younging directions. **c)** Perspective view looking west-southwest toward the Baker mine. Note the possible disruption of stratigraphy where a fault is interpreted in the centre-left of the photograph, preserving Takla Group topographically below Asitka Group exposures. It remains possible that these outcrops are part of the Asitka Group. Bedding in Asitka Group carbonate rocks (grey cliff-forming outcrops) dips in opposite directions on either side of the valley. Younging direction is upright at both locations, indicating that a north-plunging anticline underlies the valley.
d) Perspective view looking north-northeast showing exposure of Asitka and Takla groups rocks and interpreted northwest striking, north plunging F_1. Roads and workings in both photographs are part of the past-producing Baker mine.

temperatures >350°C, low-temperature thermochronological tools (e.g., zircon/apatite fission track and U-Th/He) may be required, while acknowledging that the necessary accuracy and precision may be lacking and the possibility of post-mineralization resetting is high.

5. Conclusion

Stratigraphic younging directions in eastern Stikinia reveal a large-scale, northwest-striking and plunging, northeast-vergent synclinorium-anticlinorium pair connected by a long (ca. 100 km) westward-younging limb. The northern Toodoggone region hosts several past-producing epithermal Au-Ag±Cu deposits and numerous prospects, lacking elsewhere in eastern Stikinia. In northern Toodoggone, the Black Lake intrusive suite coincides with the hinge zone of the anticlinorium and epithermal mineralization is aligned along its axial trace. Reconstruction of the Drybrough fault supports that the Lawyers and Shasta mines developed more distant and higher in the stratigraphy than the Black Lake suite intrusive contact, whereas the Baker mine is more proximal. Folding, emplacement of the Black Lake intrusive suite, and epithermal mineralization may be co-genetic, a hypothesis that may explain the uniqueness of epithermal mineralization to the Toodoggone region of eastern Stikinia and that can be tested by high-precision geochronology.

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