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Kinematic observations in the Yellowknife River Fault Zone and structures in the Jackson Lake Formation, Yellowknife Greenstone Belt, Northwest Territories[1,2]

Edith Martel, Shoufa Lin, and Wouter Bleeker

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Abstract: Detailed structural mapping has confirmed the presence of the Yellowknife River Fault Zone. This major east-dipping Archean structure marks the contact between Banting Group volcanic rocks and the ‘Timiskaming-like’ sedimentary rocks of the Jackson Lake Formation in the south, and between Kam Group and Banting Group volcanic rocks in the north. Detailed analysis led to the recognition of four generations of ductile structures (G_1 to G_4) in the study area. The Jackson Lake Formation records only three of the four generations (G_2, G_3, and G_4). The kinematics and regional significance of G_1 are poorly understood. G_2 is best explained by east-side-up, dip-slip movement with a minor sinistral shear component. G_3 and G_4 are interpreted as dextral and sinistral shear, respectively.

Résumé : La cartographie structurale detaillée a confirmé la présence de la zone de faille de Yellowknife River. Cette importante structure archéenne à pendage est marque le contact entre les roches volcaniques du Groupe de Banting et les roches sédimentaires du type «Timiskaming» de la Formation de Jackson Lake, au sud, et entre les roches volcaniques des groupes de Kam et de Banting, au nord. Des analyses détaillées ont permis de reconnaître quatre générations de structures ductiles (G_1 à G_4) dans la région à l’étude. Trois générations seulement de structures ductiles (G_2 à G_4) sont présentes dans la Formation de Jackson Lake. La cinématique et l’importance régionale de G_1 sont mal connues. On attribue G_2 à un cisaillement avec rejet est-sur-ouest, accompagné d’une composante mineure de cisaillement senestre. On attribue G_3 à un cisaillement dextre et G_4 à un cisaillement senestre.

[1] Contribution to EXTECH III
[2] Contribution to Targeted Geoscience Initiative

INTRODUCTION

The Yellowknife Greenstone Belt is a well exposed sequence of tholeiitic and calc-alkaline volcanic and sedimentary rocks unconformably overlain by a late Archean fluvial sedimentary unit, the Jackson Lake Formation. This <2605 Ma formation (Isachsen, 1992; Sircombe et al., 1999) is spatially associated with a major structure, the Yellowknife River Fault Zone (Bleeker and Ketchum, 1998). Such an association is comparable to that between 'Timiskaming-type' sedimentary rocks and major crustal 'breaks' in the Superior Province (e.g. Christie-Blick and Biddle, 1985; Thurston and Chivers, 1990). Hence, a better resolution of the structural relationships between the Jackson Lake Formation and the Yellowknife River Fault Zone is important for constraining the geological evolution of the Yellowknife Greenstone Belt and, possibly, for understanding the genesis of gold deposits in the area.

With this aim in mind, detailed mapping of the Jackson Lake Formation, the Yellowknife River Fault Zone, and surrounding areas was conducted during the summers of 2000 and 2001. The study area extends from the Sub Islands to Quyta Lake (Fig. 1), covering a north-south length of approximately 50 km. This paper summarizes field observations and preliminary kinematic interpretations.

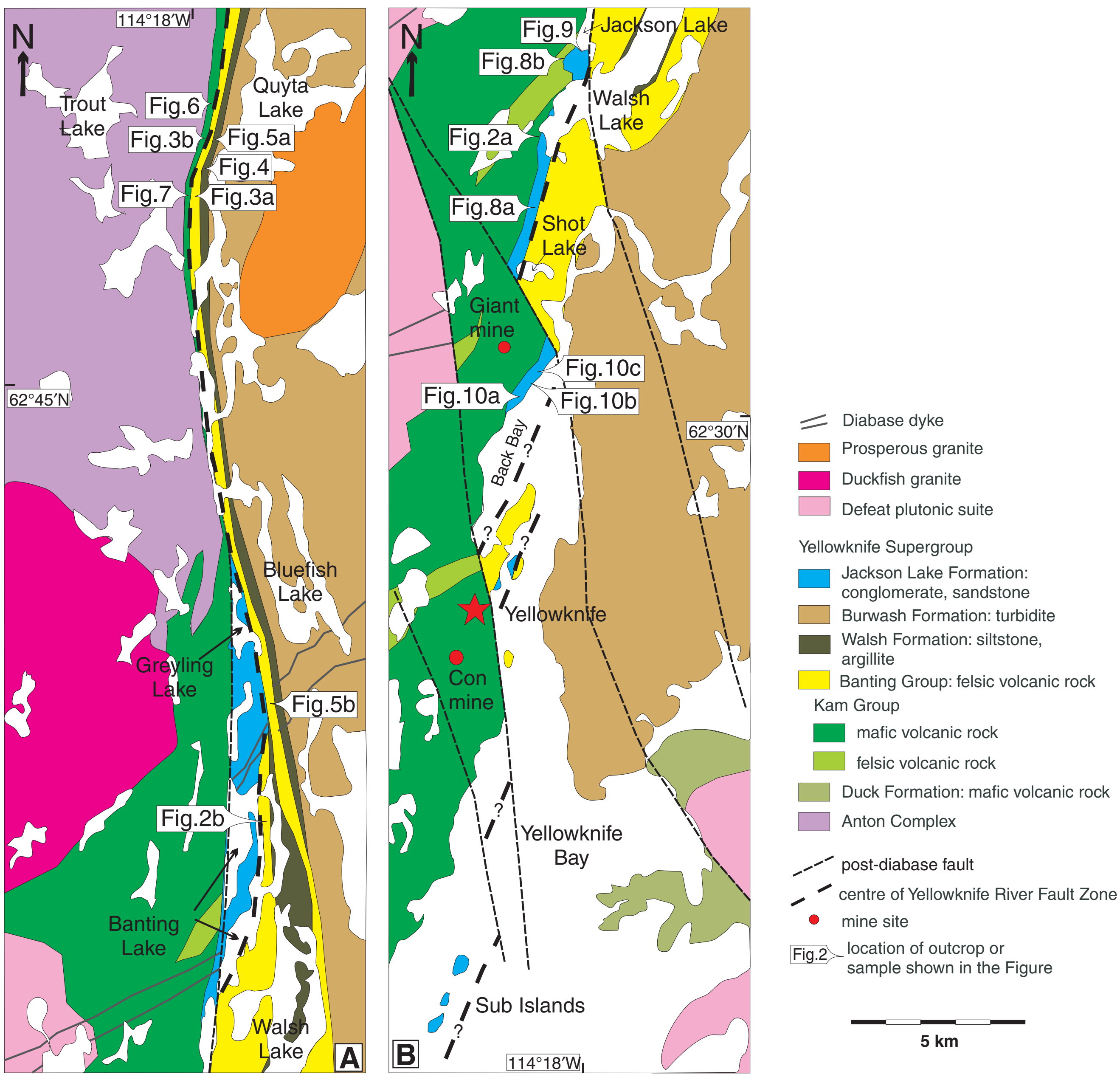

Figure 1. *Simplified geological map of the Yellowknife Greenstone Belt. Map A joins with top of map B (*modified from *Henderson and Brown (1966); Henderson (1985)).*

GEOLOGICAL SETTING

The Yellowknife Greenstone Belt is situated in the southwestern Archean Slave Province. The northeast-trending volcanic belt, which has been reoriented by proterozoic faulting into a north-south trend, is over 80 km long and is bounded to the west by granitoid rocks of varied ages (including the ca. 2.95 Ga Anton Complex (Isachsen and Bowring, 1997) and the 2.63–2.61 Ga Defeat Suite) and to the east by extensive turbidite (Yellowknife structural basin) (Fig. 1). A major portion of the greenstone belt consists of mafic volcanic flows, dykes and sills, pillow lava, and tuff of the Kam Group (ca. 2722–2700 Ma; Isachsen and Bowring, 1997). The predominantly submarine eruptive setting, tholeiitic nature of the lava, and the evidence for deposition on, and interaction with, a granitic continental basement are consistent with a continental margin rift for the Kam Group deposition (Bleeker et al., 1999; Cousens, 2000). The Banting Group lies in faulted contact with the Kam Group. It consists mainly of calc-alkaline, felsic, pyroclastic rocks (2687–2661 Ma; Isachsen, 1992) and is interpreted as a melt of juvenile hydrous mafic crust (Cousens et al., in press). In the Walsh Lake area (Fig. 1), the Banting Group occurs as two subparallel formations (Ingraham and Prosperous), separated and overlain by the Walsh Formation (Fig. 1), which consists mostly of argillite and siltstone. This geometry was previously thought to represent a primary stratigraphic relationship (Bailey, 1987; Helmstaedt and Padgham, 1986). However, observations made during this study show that these units are in shear-zone contact with each other, thus calling this interpretation into question. The Burwash Formation (ca. 2661 Ma; Bleeker and Villeneuve, 1995) occurs east of the Banting Group and the Walsh Formation. It consists of a thick pile of mudstone and greywacke turbidite that is thought to represent the main fill of a large Archean basin (Henderson, 1985). It covers a much larger area than the Kam and Banting group volcanic rocks, extending over 80 km east of the Yellowknife Greenstone Belt.

JACKSON LAKE FORMATION

The Jackson Lake Formation (<2605 Ma; Isachsen, 1992; Sircombe et al., 1999) is the youngest formation of the Yellowknife Supergroup (Helmstaedt and Padgham, 1986) and occurs as a steeply dipping, east-younging panel between the Kam Group to the west and the Banting Group to the east. The Kam Group–Jackson Lake Formation contact is a well preserved, although locally sheared, angular unconformity (Fig. 2a) that cuts down through the stratigraphy of the Kam Group toward the north (Henderson and Brown, 1966). The Jackson Lake Formation–Banting Group contact represents a

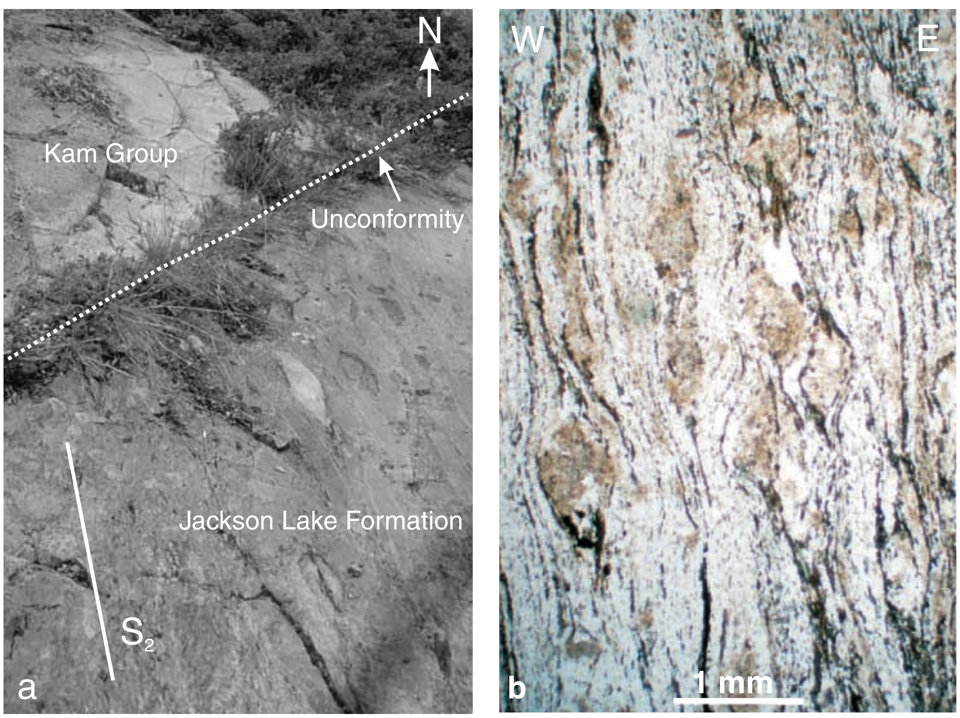

***Figure 2. a**) Angular unconformity between east-facing pillow basalt of the Kam Group and basal breccia of the Jackson Lake Formation. South of Walsh Lake. Note that the foliation S_2, defined by flattening of the clasts, transects the unconformity counterclockwise. **b**) Photomicrograph of a mylonite in the Yellowknife River Fault Zone. Section cut perpendicular to foliation and parallel to lineation. East of Banting Lake. Note the shear bands around the feldspar porphyroclasts that indicate east-side-up movement. Plane light.*

major stratigraphic discontinuity that defines the Yellowknife River Fault Zone (Bleeker and Ketchum, 1998). Our field observations confirm the presence of a stratigraphic discontinuity and further suggest the presence of a major deformation zone that encompasses the Jackson Lake Formation–Banting Group contact (Fig. 2b).

The Jackson Lake Formation consists of a locally developed basal breccia overlain by conglomerate, pebbly sandstone, crossbedded sandstone, and scarce argillite. To the north it is dominated by sandstone and to the south, by conglomerate. The conglomerate contains a wide variety of subangular to well rounded clasts (e.g. granitic pebbles, jasper, fuchsite-rich clasts, quartz, basalt, quartz-feldspar porphyry, carbonate, dark chert, and argillite). Microscopic observations show the ubiquitous presence of white mica, chlorite, and chloritoid in the formation, indicating greenschist metamorphic grade.

On the basis of stratigraphic and lithological study of the Jackson Lake Formation, and similarities with Timiskaming-type sedimentary rocks of the Superior Province, the formation has been interpreted as a fluvial–alluvial fan deposit (Henderson, 1985), presumably deposited in a tectonically controlled basin (e.g. Helmstaedt and Padgham, 1986; Mueller and Donaldson, 1994).

STRUCTURAL FRAMEWORK

The Yellowknife River Fault Zone is a north-trending structure. It appears to bend toward the southwest in the south, spatially associated with the eastern contact of the Jackson Lake Formation, and, where the Jackson Lake Formation is absent, with the Kam Group–Banting Group contact. The 10 to 30 m wide mylonite zone defining the fault zone (Fig. 2b) has been traced for over 30 km, from Shot Lake through the Banting Lake area, to the western shore of Quyta Lake, where it is especially well exposed (Fig. 1). The actual zone of intense deformation is much wider (>400 m wide), extending both east and west of the Jackson Lake Formation–Banting Group contact. Recently acquired geophysical data (magneto-telluric) reveal an anomalously strong, listric, east-dipping conductor that extends all the way to the mantle (A. Jones and X. Garcia, pers. comm., 2002). This conductor appears to be spatially coincident with the Yellowknife River Fault Zone, but it could also reflect the graphitic composition of the nearby Walsh Formation. Regardless of its nature, it delineates a crustal-scale structure.

Four generations of ductile structures (G_1 to G_4) have been recognized in the study area on the basis of fold and foliation overprinting relationships (Fig. 3). Associated folds, foliations, and lineations, where present, are named F_1 to F_4,

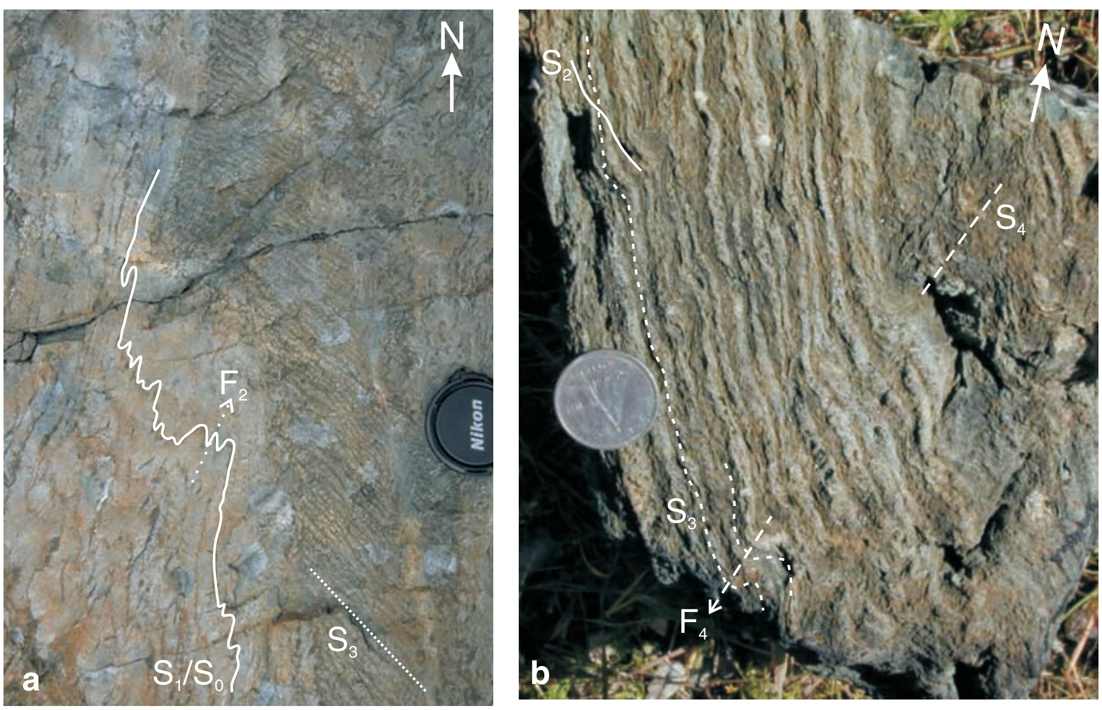

Figure 3. a) *S-shaped F_2 folds overprint the S_1 foliation in a felsic volcanic rock of the Banting Group. The folds are overprinted by an S_3 foliation. West of Quyta Lake.* ***b)*** *Sample of a strongly deformed rock (probably a mafic to intermediate volcanic rock of the Kam Group) from the Yellowknife River Fault Zone near the Kam Group–Banting Group contact. West of Quyta Lake. Three generations of structures are present. S_2 is preserved in the microlithons of the S_3 crenulation cleavage (enveloping surface approximately 350°). The S_3 foliation is folded, forming F_4 folds with a locally developed S_4 axial planar foliation oriented approximately 040°. In this particular sample, the S_1 foliation is observed only at the microscopic scale.*

S_1 to S_4, and L_1 to L_4 respectively. The term 'generation' (G) is used in this study instead of deformation event (D) because the significance of each generation with respect to discrete deformation episodes is not yet well constrained. Thus, more than one generation of the structures may have developed during a single episode of progressive deformation. The physical characteristics of each generation of ductile structures vary depending on the host-rock type and proximity to the Yellowknife River Fault Zone, the locus of the most intense deformation. The four generations of ductile structures recognized in the study area are described below. Structures outside the Jackson Lake Formation are first described and subsequently correlated with those observed in the Jackson Lake Formation.

G_1 structures

The earliest generation of structures (G_1) recognized within or near the Yellowknife River Fault Zone comprises a crenulated, bedding-parallel, S_1 foliation defined by the alignment of mica. This foliation was observed in the field (Fig. 3a) and confirmed at a microscopic scale within microlithons of the later S_2 foliation (Fig. 4). The kinematics and significance of the G_1 deformation are uncertain.

G_2 structures

G_2 is well developed both within and outside the Yellowknife River Fault Zone. It produced an S_2 foliation consistently oriented clockwise (~20º) to the shear-zone boundary and bedding. In the felsic volcanic beds of the Banting Group, S_2 is a continuous fabric, whereas in the more pelitic (mica-rich) beds of the sedimentary Walsh and Burwash formations, S_2 is a strongly developed differentiation layering (Fig. 5a). S_2 is axial planar to small- and large-scale, moderately to steeply northeast-plunging, S-shaped F_2 folds of both bedding and S_1 (Fig. 3a). Stretching (L_2) and intersection (L_{0-2}) lineations associated with S_2 are subparallel, plunging steeply to either the north or the south. In thin sections oriented parallel to the stretching lineation, shear-sense indicators such as σ- and

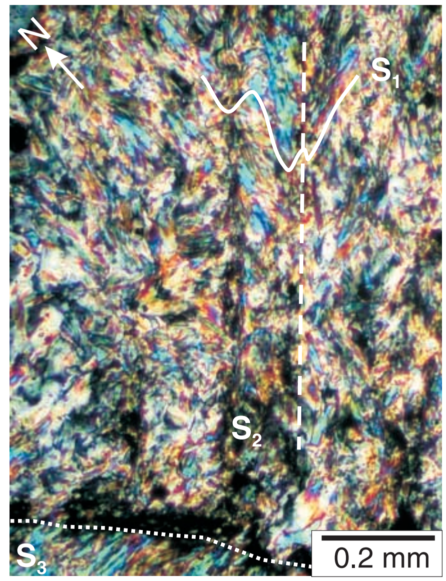

Figure 4. *Photomicrograph of an argillaceous bed of the Walsh Formation showing the S_1 foliation within the microlithons of the S_2 differentiation layering. S_1 is defined by the alignment of micas and is crenulated by S_2. S_1 and S_2 have been overprinted by S_3. Crossed nicols. West of Quyta Lake.*

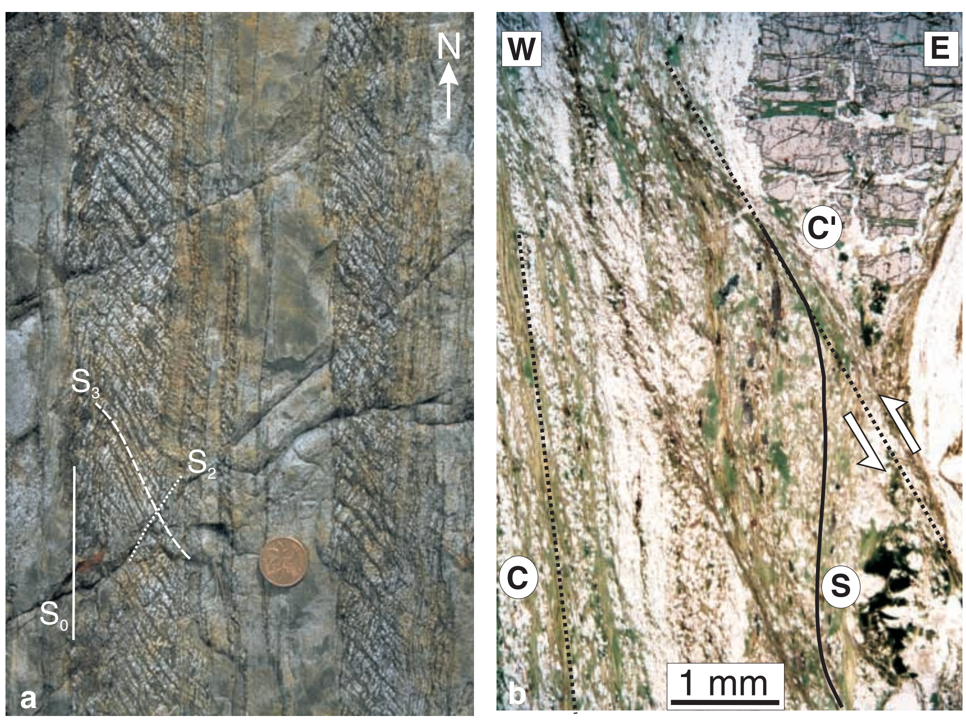

Figure 5.

a) *S_2 differentiation layering oriented clockwise to bedding in sandstone and siltstone beds of the Walsh Formation, overprinted by a spaced S_3 (counterclockwise to S_0). West of Quyta Lake. Note that the S_3 foliation is developed exclusively within the pelitic beds.* ***b)*** *Photomicrograph of an amphibolite-grade volcanic rock of the Banting Group. Section cut perpendicular to foliation and parallel to lineation. C' shear bands indicate east-side-up movement. North of Banting Lake. Plane light.*

δ-type rotated porphyroblasts and C' shear bands are commonly observed along the length of the Yellowknife River Fault Zone, and are especially well developed in the Banting Group. They consistently show an overall east-over-west motion (Fig. 5b). This, together with the 'S' asymmetry of the F_2 folds and the orientation of S_2 clockwise to earlier fabrics (S_1 and the shear-zone boundary) indicate that east-side-up dip-slip motion with a minor sinistral shearing component prevailed during G_2.

G_3 structures

G_3 produced distinctive structures identified ubiquitously along the Yellowknife River Fault Zone. The S_3 foliation is observed only within or adjacent to the shear zone where it becomes a very strong differentiated crenulation cleavage. S_3 is best developed in the mafic to intermediate units of the Kam Group (Fig. 3) and in the more pelitic beds of the Walsh and the Burwash formations (Fig. 5a). It is also observed, but less commonly, in the Banting Group. It is oriented counterclockwise to bedding, S_2, and the shear-zone boundary, and is axial planar to open and upright, steeply plunging, Z-shaped F_3 folds (Fig. 6). A steep intersection lineation (L_{3-0}) is observed locally. The orientation of S_3 with respect to earlier structures (S_2 and the shear-zone boundary) combined with the F_3 fold asymmetry indicate a dextral shear component localized along the Yellowknife River Fault Zone during G_3.

G_4 structures

G_4 structures occur in the vicinity of the Yellowknife River Fault Zone. The G_4-related folds and foliation occur locally in the Kam and Banting groups, but are poorly developed in the Walsh and Burwash formations. Within the fault zone, S_4 is strongly developed and is defined by a coarsely spaced cleavage that parallels the shear-zone boundary and crenulates the S_3 foliation. S-shaped F_4 folds of the S_3 foliation are common and generally plunge steeply to moderately to the northeast (Fig. 3b). Where the deformation is most intense, C' shear bands associated with S_4 are developed, indicating sinistral shear during G_4 (Fig. 7). Adjacent to the shear zone, the S_4 foliation is oriented northeast, approximately parallel to the S_2 foliation. As a result, S_4 reinforces the pre-existing S_2, but no S_4 crenulation cleavage is developed outside the shear zone, except within F_4 fold-hinge areas, where it crenulates S_2 and S_3 if present.

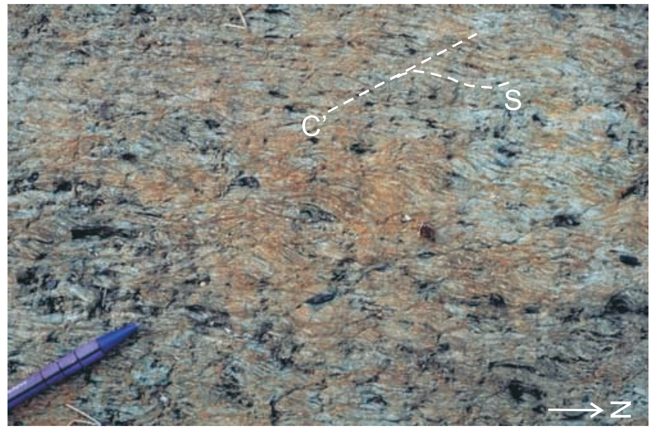

***Figure 7.** C' shear bands in mafic (?)volcanic rocks of the Kam Group. The shear bands are associated with S_4, developed where the G_4-related strain is most intense, and indicate sinistral shear. West of Quyta Lake.*

***Figure 6.** Z-shaped F_3 folds in intermediate volcanic rocks of the Kam Group trending north-northwest with a well developed differentiated axial planar foliation (S_3). West of Quyta Lake.*

CORRELATIVE STRUCTURES IN THE JACKSON LAKE FORMATION

The sequence of deformation (G_1 to G_4) was established in the study area, and more precisely in the vicinity of the Yellowknife River Fault Zone, on the basis of well preserved overprinting relationships (Fig. 3 to 7). To constrain the timing of deformation and understand the significance of the structures described above, an effort is made to correlate the G_1 to G_4 generations of structures with those observed in the Jackson Lake Formation.

G_2 structures in the Jackson Lake Formation

As mentioned above, the Jackson Lake Formation is spatially associated with the Yellowknife River Fault Zone and, to the west, lies unconformably on Kam Group volcanic rocks. The earliest generation of structures recognized in the Jackson Lake Formation is characterized by a penetrative foliation, generally oriented parallel or clockwise to bedding (010º–030º). This foliation is dominant on about 75% of the Jackson Lake Formation exposures and is defined by flattening of the clasts in the conglomerate (Fig. 2a, 8a) and by deformed quartz grains in the sandstone. Associated with it is a steeply plunging stretching lineation (Fig. 8a), and outcrop- and macroscopic-scale Z- and S-shaped folds. The folds generally plunge to the north (Fig. 8c) and are best outlined by the folded unconformity (Fig. 8b). This earliest foliation in the

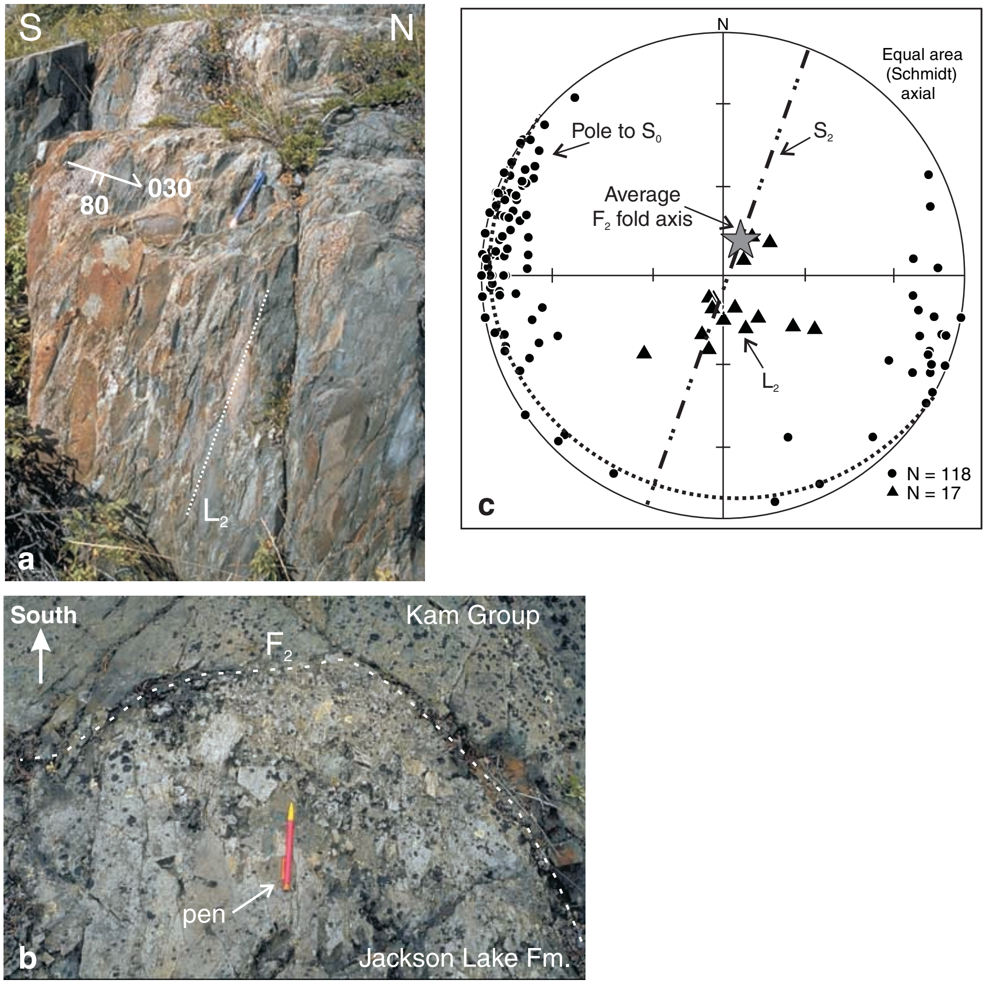

Figure 8. *G_2 structures in the Jackson Lake Formation.* ***a)*** *On the S_2 foliation plane (030°/80°E), the stretched clasts pitch steeply to the south and define the L_2 lineation in the conglomerate. West of Shot Lake. Pen in the centre for scale.* ***b)*** *F_2 fold in the unconformable contact between the Kam Group and the Jackson Lake Formation. South of Jackson Lake. S_2 (parallel to the pen) is axial planar to the fold.* ***c)*** *Equal-area, lower-hemisphere projection of poles to S_0, the average S_2 foliation plane, and L_2 lineations. The star is the average F_2 fold axis, or the pole to the girdle defined by the poles to bedding (dotted line).*

Jackson Lake Formation appears to be correlative with S_2 described above, as both foliations are penetrative fabrics oriented clockwise to the shear-zone boundary. This interpretation is supported by the fact that this foliation in the Jackson Lake Formation transects the Kam Group–Jackson Lake Formation unconformity (Fig. 2a), where it becomes a crenulation cleavage of S_1 in the Kam Group. The presence of an angular unconformity at the base of the Jackson Lake Formation is consistent with this interpretation, because it indicates that at least the generation of deformation responsible for the tilting of the Kam Group stratigraphy took place prior to deposition of the Jackson Lake Formation. Where the unconformity is sheared, shear-sense indicators show west-over-east dip-slip component. If this shearing event was contemporaneous with the G_2-related, east-side-up deformation along the eastern margin of the Jackson Lake Formation, then the Jackson Lake Formation was moving down relative to the volcanic rocks on both sides. This can explain, a least in part, the preservation of the formation in the area.

G_3 structures in the Jackson Lake Formation

The main foliation (S_2) in the Jackson Lake Formation is overprinted by a differentiated crenulation cleavage developed exclusively in the pelitic beds and oriented counterclockwise to S_0 and S_2 (Fig. 9). This foliation is correlated with S_3 recognized in the vicinity of the Yellowknife River Fault Zone, on the basis of similar structural style (differentiated crenulation cleavage) and orientation (counterclockwise) relative to the shear-zone boundary. These relationships suggest

Figure 9. Photomicrograph showing a chevron cleavage pattern between S_2 (clockwise to S_0) and S_3 (counterclockwise to S_0) in the Jackson Lake Formation. The latter occurs only in the pelitic beds. Plane light. South of Jackson Lake.

dextral shear (*see* Fig. 5a, 9). The S_2–S_3 spatial relationship is similar to the chevron cleavage pattern described by Henderson (1997), in which the S_2 foliation is preserved in the more competent sandstone and the S_3 differentiated crenulation cleavage is developed in less competent pelite (Fig. 9). S_3 is not widely observed because mica-rich facies favorable for the development of S_3, such as pelite, are not abundant.

G_4 structures in the Jackson Lake Formation

In the southern portion of the Jackson Lake Formation outcrop area (conglomerate-dominated), the main foliation (S_2) is overprinted clockwise by a spaced foliation defined by the preferred alignment of micas (Fig. 10a). The foliation is correlative with S_4 given their similar structural style and relative orientation. S-shaped F_4 folds are contemporaneous with S_4. Where S_4 is strongly developed, it is locally crenulated by a later foliation (S_{4b}), which is physically similar to S_4 (Fig. 10b). Also, S_4 is observed to be folded into S-shaped F_{4b} folds (Fig. 10c). These observations are interpreted to indicate progressive sinistral shearing during the late stages of G_4.

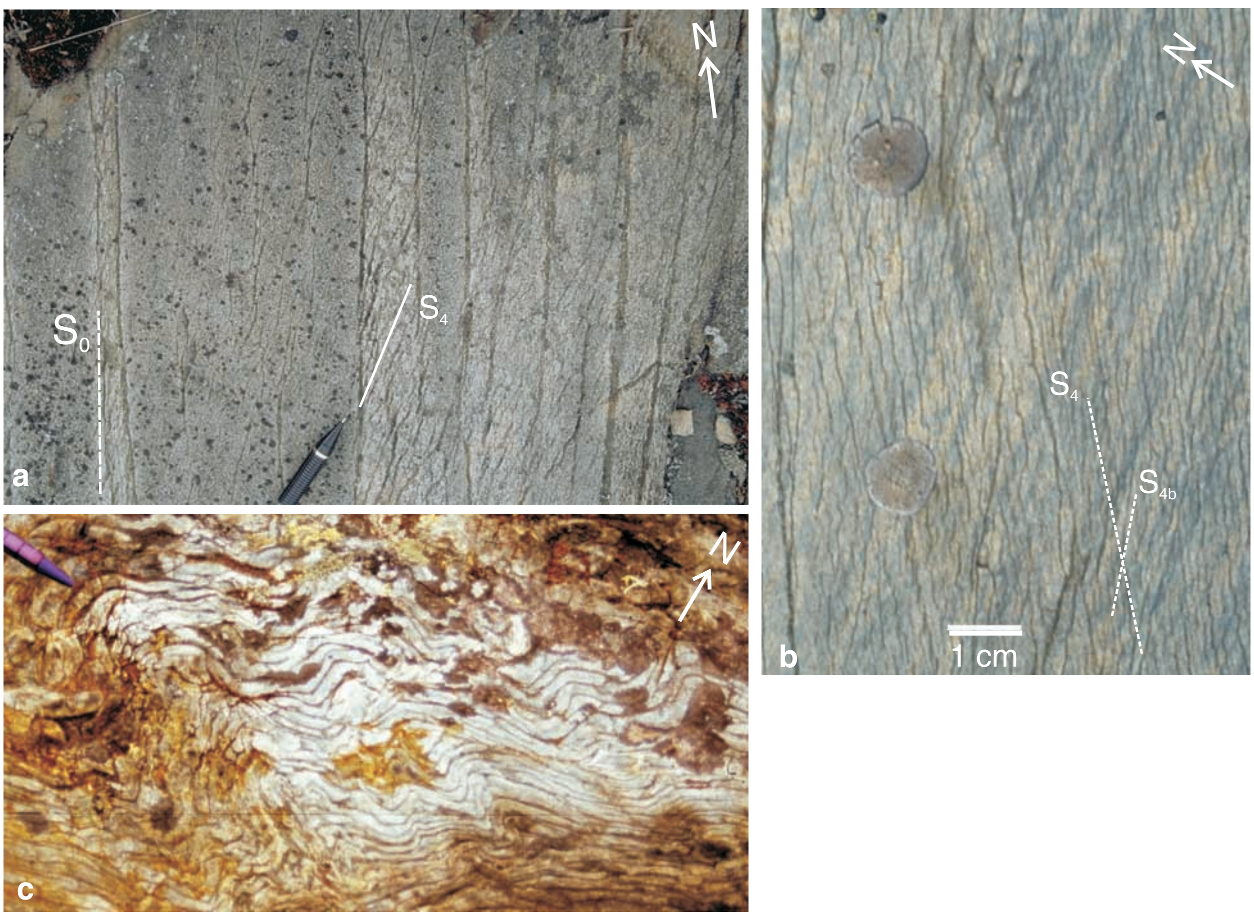

*Figure 10. G_4 structures in the Jackson Lake Formation. **a)** S_4 spaced foliation oriented clockwise to bedding. **b)** S_{4b} foliation oriented clockwise to S_4. **c)** S-shaped F_{4b} folds observed where S_4 is most intensely developed. All outcrops are from the Giant mine site, on the northwest shore of Back Bay.*

In summary, three generations of ductile structures are recognized in the Jackson Lake Formation. They are correlative with G_2, G_3, and G_4 structures observed within the adjacent volcanic rocks and along the Yellowknife River Fault Zone.

CORRELATION WITH REGIONAL-SCALE AND DEPOSIT-SCALE STRUCTURES

Correlation with regional-scale structure

Previous structural studies concluded that the existing geometry in the Yellowknife Domain (Burwash Formation turbidite east of the Yellowknife Greenstone Belt; *see* Fig. 1) resulted from two main phases of regional deformation, D_1 and D_2 (Henderson, 1943, 1985; Bleeker and Beaumont-Smith, 1995; Bleeker, 1996). D_1 produced high-amplitude, upright, doubly plunging F_1 folds. An associated S_1 axial planar foliation as well as a steeply plunging stretching lineation (L_1) are preserved locally. The kinematics of D_1 is not well understood. D_2 produced the dominant foliation in the turbidite (S_2) that is axial planar to steeply plunging, northwest-trending F_2 folds. The F_2 folding is interpreted to result from dextral transpression. Following the folding, D_2 deformation became localized within discrete dextral shear zones. A D_3 event has been documented that produced a locally developed, coarsely spaced, subvertical crenulation cleavage (Bleeker and Beaumont-Smith, 1995; Henderson, 1997; Davis and Bleeker, 1999). However, the significance and kinematics of D_3 are poorly understood.

We tentatively correlate G_1 with D_1, whereas G_2 and G_3 are both associated with D_2. The suggestion that G_2 structures are comparable to D_2 is based on field observations that the regional S_2 (the dominant foliation in the turbidite; Bleeker and Beaumont-Smith, 1995, and references therein) can be traced into S_2 in the study area. The kinematics of G_3 structures is comparable to that of the regional late-stage D_2, both are characterized by localized dextral shearing (Bleeker and Beaumont-Smith, 1995; this study). Whether the regional D_3 can be correlated with G_4 is uncertain, partly because the kinematics of the former is unknown.

Correlation with deposit-scale structure

In the Kam Group, a deposit-scale structural study (Siddorn and Cruden, 2000) concluded that at least two main deformation events are responsible for the geometry of the Con and Giant gold mines in Yellowknife. The main deformation event (D_2) is interpreted as east-west compression of the deposits, with most D_2 shortening focused on a series of deformation zones that host the gold mineralization (e.g. Campbell, Con, and Giant deformation zones). This deformation event is kinematically consistent with the G_2 generation of deformation observed in the study area. Thus D_2 in the mines is tentatively correlated with G_2 in our study area. This correlation, if correct, is important because syn-D_2 mineralization observed in the gold deposits is potentially present in the Jackson Lake Formation. Anomalous gold values have been documented in the Sub Island exposures (Fig. 1) of the Jackson Lake Formation (J.A. Kerswill, pers. comm., 2002; Hoard, 2002). Furthermore, given the depositional environment of the formation in which most sediments are derived from the underlying Kam Group, pre-D_2 mineralization can potentially occur as paleoplacer gold deposits in the Jackson Lake Formation.

SUMMARY AND CONCLUSIONS

Four generations of ductile structures (G_1 to G_4) are observed in the vicinity of the Yellowknife River Fault Zone, but only G_2, G_3, and G_4 have been recognized in the Jackson Lake Formation. The tectonic significance of G_1 is uncertain. Nonetheless, the G_1 event could be responsible for the formation of a basin in which the Jackson Lake Formation sediments were deposited. G_2 is the first generation of deformation observed in the Jackson Lake Formation and is interpreted to be oblique shear (east-side up and minor sinistral component) resulting from east-southeast–west-northwest compression. G_2 is tentatively correlated with the main stage of regional D_2. G_3 is interpreted as dextral shear localized along the Yellowknife River Fault Zone, possibly correlative with late-stage D_2 dextral shear zones documented at the regional scale. Syn-D_2 and pre-D_2 gold mineralization at the Giant and Con mines is potentially present in the Jackson Lake Formation. G_4 is interpreted as sinistral shear along the Yellowknife River Fault Zone, but it is not yet possible to correlate the G_4 structures observed in the Yellowknife Greenstone Belt with either regional- or deposit-scale structures.

ACKNOWLEDGMENTS

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