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Authors' addresses

***William A. Turner** (allan_turner@gov.nt.ca)*
***Leonard P. Gal** (len_gal@gov.nt.ca)*
C.S. Lord Northern Geoscience Centre
P.O. Box 1500, 4601-B 52nd Avenue
Yellowknife, Northwest Territories X1A 2R3

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Regional structural data from the Hay River area, Northwest Territories, with emphasis on the Pine Point mining camp

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Abstract: A regional study undertaken south of Great Slave Lake, Northwest Territories, focused on evaluating evidence for structural control on mineralization at Pine Point. Relatively consistent northeast-southwest (055°) and northwest-southeast (125°, 140°, 150°, and 160–165°) joint sets were observed in the study area. A dominant east-west (085°) joint set was observed in one domain. The orientation of the 055° set is close to that of the Great Slave Lake Shear Zone (045° at Pine Point) and the Hay River Fault (055°; west side of study area).

Previous studies conducted on ore-mineral paragenesis at Pine Point proved that hydrothermal dolomite occurred concurrently with the ore-deposition event. This study demonstrates that fracturing at Pine Point pits largely postdated dolomitization, and therefore ore deposition. Furthermore, no structural controls on mineralization were observed in the pits, and are therefore not considered a primary mechanism for ore emplacement in the Pine Point orebodies.

Résumé : Une étude régionale entreprise au sud du Grand lac des Esclaves (Territoires du Nord-Ouest) visait principalement à évaluer les indices d'un contrôle structural sur la minéralisation à Pine Point. Dans la région à l'étude, on a observé des réseaux de diaclases orientés de manière relativement cohérente suivant des orientations nord-est–sud-ouest (055⌢) et nord-ouest–sud-est (125°, 140⌢, 150⌢ et 160-165⌢). Un réseau dominant de diaclases d'orientation est–ouest (085⌢) a été observé dans un domaine. L'orientation du réseau à 055⌢ se rapproche de celle de la zone de cisaillement du Grand lac des Esclaves (045⌢ à Pine Point) et de celle de la faille de Hay River (055⌢; dans l'ouest de la région à l'étude).

Les études antérieures sur la paragenèse du minerai à Pine Point ont démontré que la dolomite hydrothermale s'est formée au cours de l'épisode minéralisateur. La présente étude révèle que la fracturation dans les fosses de la mine Pine Point est survenue bien après la dolomitisation et, par conséquent, après la minéralisation. En outre, aucun contrôle structural sur la minéralisation n'a été observé dans les fosses de la mine; il ne s'agirait donc pas d'un mécanisme de mise en place primaire du minerai dans les amas minéralisés de Pine Point.

INTRODUCTION

The C.S. Lord Northern Geoscience Centre conducted a structural investigation in the vicinity of Great Slave Lake, southern Northwest Territories, during the 2002 field season. This study is part of a Targeted Geoscience Initiative entitled 'Potential for carbonate-hosted Pb-Zn (MVT) deposits in northern Alberta and southern Northwest Territories', a collaborative project between the C.S. Lord Northern Geoscience Centre, the Geological Survey of Canada, and the Alberta Geological Survey. The goals of the multidisciplinary project are to delineate the distribution and describe the origin of known Mississippi Valley–type Pb-Zn deposits in the Pine Point mining camp, and to investigate the potential for further undiscovered orebodies of similar type in the southern Northwest Territories and northern Alberta. To accomplish these goals, the host-rock types, associated structures, alteration, and geochemical signatures of the Pb-Zn deposits were examined to determine the conduits and origins of the mineralizing fluid(s).

A summary of the observations and interpretations that resulted from this reconnaissance structural study is presented in this paper. The aims of the study were to 1) examine surface structures at a regional scale, and at a deposit scale at the Pine Point minesite, and evaluate evidence for the involvement of basement structures in the formation of the observed surface structural features; and 2) look for evidence of syn- or epigenetic structures with respect to ore deposition at Pine Point. The study area extends from the southern shore of Great Slave Lake to the Northwest Territories–Alberta boundary, and from the Heart Lake fire tower (approx. 50 km northwest of Enterprise) to the Little Buffalo River, west of Fort Resolution (Fig. 1, 2).

REGIONAL GEOLOGICAL SETTING

The area of study focuses on the northeastern section of the Interior Platform, a relatively undisturbed sedimentary sequence in the southern Northwest Territories (Fig. 1; Douglas et al., 1970). The Phanerozoic stratigraphic section that constitutes the Interior Platform thickens westward to its border with the Cordillera foreland. To the east, it thins to an erosional edge that exposes Precambrian granite and metamorphic rocks of the Canadian Shield. Within the study area, the Interior Platform hosts the Presqu'ile barrier, a carbonate reef complex that formed during the Givetian (Middle Devonian; Rhodes et al., 1984; Meijer Drees, 1994). The Presqu'ile barrier outcrops on the southern shore of Great Slave Lake (Fig. 1), and regionally dips to the west at 1.9 m/km (Rhodes et al., 1984). This barrier extends to the southwest for approximately 400 km, and varies between 20 and 90 km in width (Qing and Mountjoy, 1994). Development of the Presqu'ile barrier restricted seawater circulation, giving rise to evaporites and lesser carbonate units in the Elk Point Basin to the south (Fig. 1).

Rhodes et al. (1984) proposed that extensive conduit systems (paleokarsts) formed in select carbonate facies along the strike of the Presqu'ile barrier complex. These paleokarsts host almost 100 individual Pb-Zn orebodies (Randall et al., 1985), and make the Pine Point area a world-class Mississippi Valley–type mining camp.

Regional stratigraphy

Several authors have described the stratigraphy south of Great Slave Lake. A brief review is presented below and the reader should consult the references cited for more

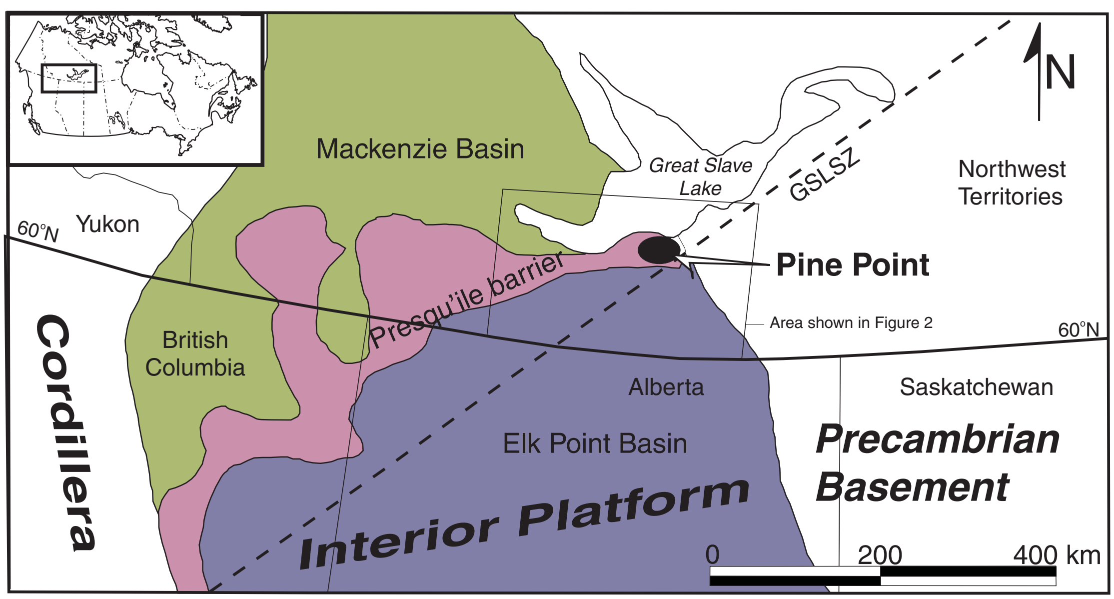


*Figure 1. Simplified Devonian geology of northwestern Canada, showing the location of the Presqu'ile barrier with respect to the Mackenzie and Elk Point basins (*modified after *Qing and Mountjoy, 1994). Abbreviation: GSLSZ, Great Slave Lake Shear Zone.*

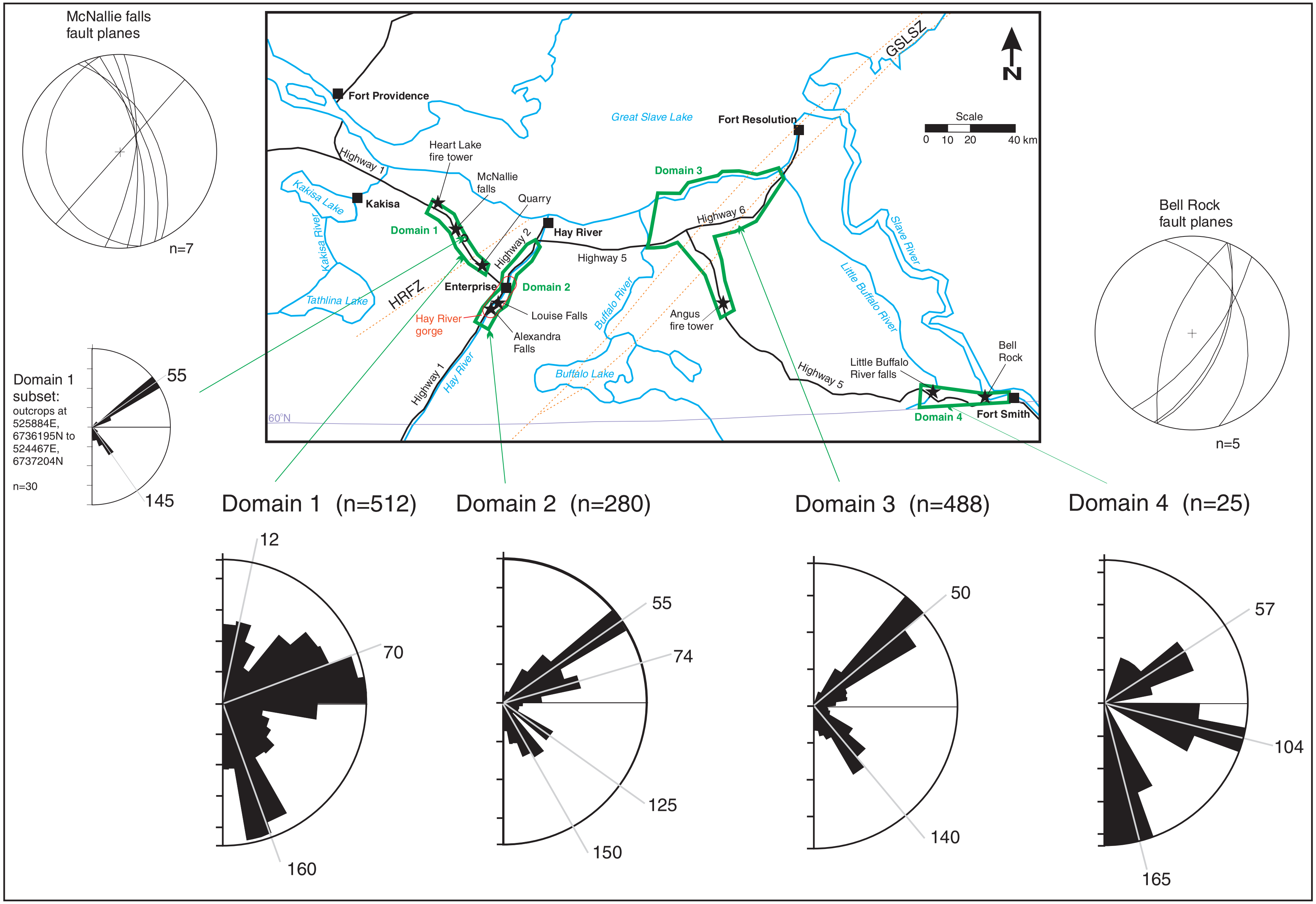


Figure 2. *Location of the study area and Domains 1 to 4. Rose diagrams of joints measured within each domain are indicated, along with the interpreted dominant joint-set orientations. Data from each domain were plotted in 10° azimuth increments. A subset of Domain 1, comprising two outcrops southwest of McNallie falls, is also illustrated. Equal-angle sterographs, with great circles representing fault or slip planes at McNallie falls (left) and Bell Rock (right), are also shown.* See *text for discussion. Abbreviations: GSLSZ, Great Slave Lake Shear Zone; HRFZ, Hay River Fault Zone.*

information. The Proterozoic basement in the Pine Point area is unconformably overlain by siliciclastic rocks of the Old Fort Island Formation, and carbonate and siliciclastic rocks of the Mirage Point Formation, both of which are interpreted as Ordovician or older in age (Douglas, 1959; Belyea and Norris, 1962; Norris, 1965). Unconformably overlying the Mirage Point Formation are carbonate rocks of the Chinchaga Formation, which is lower Middle Devonian (Eifelian) in age (Norris, 1965).

The Presqu'ile carbonate barrier and its associated rock types have been studied by Law (1955), Belyea and Norris (1962), Richmond (1965), Norris (1965), Skall (1975), Rasmussen (1981), Lantos (1983), Rhodes et al. (1984), and Norris and Uyeno (1998), among others. The rocks conformably overlie the Chinchaga Formation, and are divided into eight formations that represent five paleoenvironments. These environments are 1) the Keg River Formation, which represents the lower carbonate platform; 2) a carbonate barrier complex, composed of lower and upper sections termed the Pine Point and Sulphur Point formations; 3) the evaporitic sequence of the Muskeg Formation, which is equivalent to a back-barrier environment; 4) the Buffalo River and Windy Point formations, which were deposited to the north of the barrier in a fore-barrier environment; and 5) the Watt Mountain and Slave Point formations, overlying the barrier and its equivalents.

West of the Pine Point area, in the vicinity of the Hay River, is the erosional edge of the Upper Devonian Hay River Formation (Jamieson, 1967). Meijer Drees (1993) further defined this formation to encompass all beds between the top of the Slave Point Formation and the base of the Twin Falls Formation. The siliciclastic and carbonate rocks associated with the Hay River Formation, which incorporates the Escarpment Member, and the unconformably overlying Twin Falls Formation, which includes the Alexandra Member, have been studied by Cameron (1918), Belyea and McLaren (1962), Jamieson (1967), Williams (1977), Hadley (1987), Hadley and Jones (1990), and Bellow (1993). Although these units have been extensively examined, the formal classification of the different rocks into formation, member and facies status remains a matter of considerable debate.

DATA COLLECTION

Collection of regional structural data was affected by sparse outcrop in the study area. Rock exposures are typically restricted to quarries, road cuts, pits, lakeshores, and riverbanks. Mesoscopic structures, such as fault zones, were rarely observed. The field study, therefore, focused primarily on the measurement of joints, as they were the only abundant structural element observed. Although much controversy is associated with the interpretation of joints (Pollard and Aydin, 1988), regional studies such as those conducted on the Appalachian Plateau of Pennsylvania (Nickelsen and Hough, 1967) and in Alberta (Babcock, 1973, 1974, 1975; Pana, 2002), have reported success in relating joint sets to major structural trends and basement features.

Joints measured in this study were restricted to those that had straight to slightly curved surfaces, were continuous, and occurred in groups of several fractures of the same general orientation (Fig. 3a). Thus, they generally belong to the 'systematic joint' classification of Hodgson (1961). Mineral fillings, strong iron oxidation or other stains, nonvertical dips, and dislocations of bedding surfaces were noted, if present. Care was taken to avoid joints adjacent to pits and along road cuts that were obviously the result of blasting; plumose structures were not recorded, as they may have formed as a result of blasting in these areas. However, it is possible that some man-made fractures were included in the data set, as discussed below. Joints selected were typically straight and had spacings on the decimetre to metre scale.

At some stations, particularly those where outcrop exposure was limited, all selected systematic joints were measured along a transect. In large areas of outcrop, representative measurements were made of the systematic joints.

In addition to joint sets, other structures were noted and measured. These included fault zones as well as scattered occurrences of slickensides and grooved joint surfaces that indicated slip.

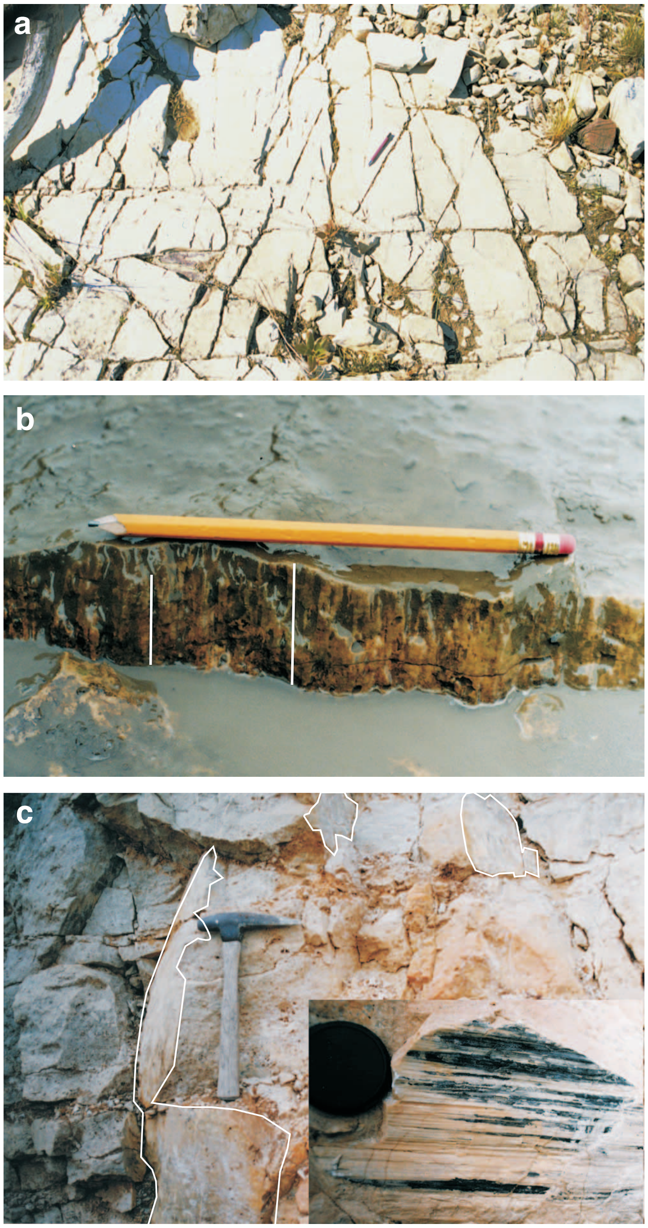
The study area was divided into four geographic domains:

1. Domain 1 encompasses the area around Highway 1, from just northwest of Enterprise to the Heart Lake fire tower (Fig. 2). All measurements along this transect were made along road cuts and outcrops of the lower Alexandra Member of the Twin Falls Formation.
2. Domain 2 spans a section of the Hay River, from south of Alexandra Falls to the junction of Highways 2 and 5 (Fig. 2). This domain includes measurements made at pits and riverside outcrops in both the Hay River (Escarpment Member) and Twin Falls (upper Alexandra Member) formations.
3. Domain 3 covers the Pine Point area, from Sulphur Point on Great Slave Lake to the Little Buffalo River, and south to the Angus fire tower on Highway 5 (Fig. 2 and 4). This domain encompasses the open pits accessible at Pine Point, lakeshore exposures, and roadside outcrops of the Sulphur Point and Pine Point formations.
4. Domain 4 encompasses two outcrop areas, at Bell Rock on the Slave River and at Little Buffalo River falls. Both areas expose the Chinchaga Formation (Norris, 1965; Fig. 2).

Structural measurements are reported for the four domains described above. Data from each domain were plotted on half circle rose diagrams (Fig. 2, 4).

RESULTS

We observed 1305 joints, two fault zones, rare instances of mineral slickensides, and fracture fillings of calcite (and/or dolomite and iron-sulphide minerals) across the study area.



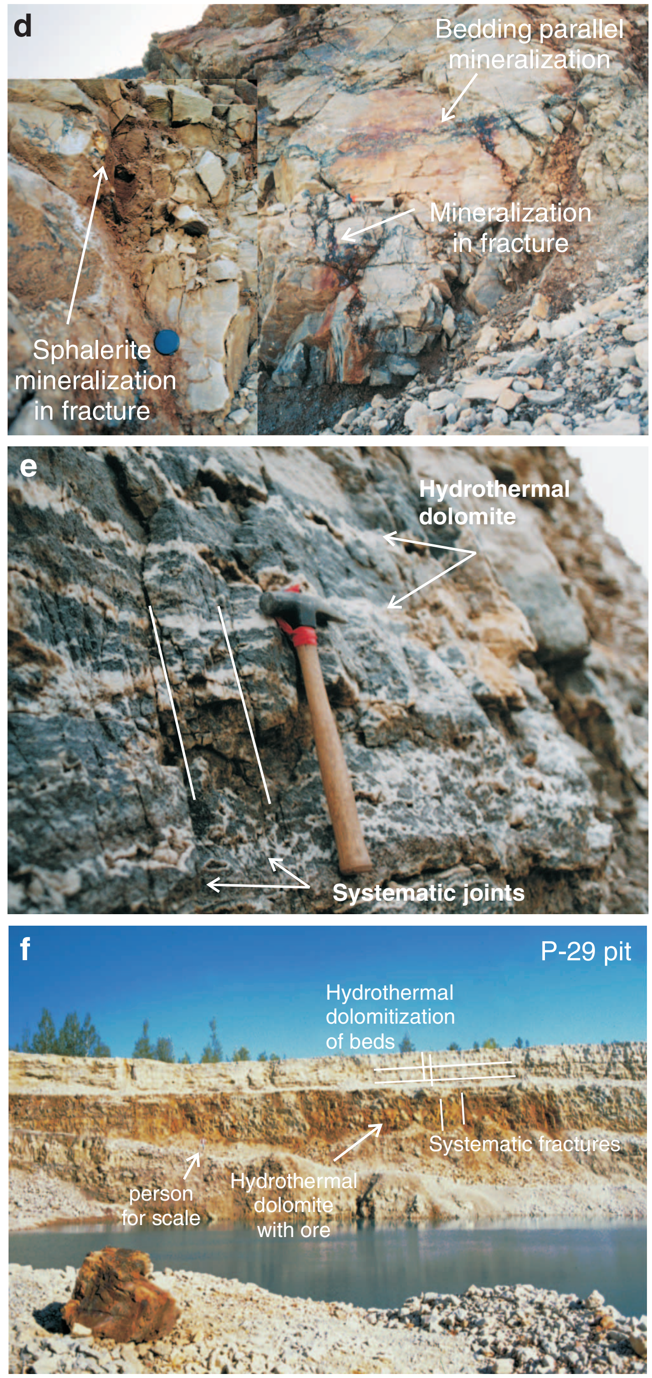


***Figure 3. a**) Typical outcrop exposure on the shore of Great Slave Lake, near Pine Point (Domain 3). Bedding is approximately horizontal, and is cut by three sets of subparallel joints (pencil for scale). **b)** Grooves on fracture surface just upstream from Alexandra Falls (Domain 2). The grooves and striations plunge down dip, but no relative displacement indicators are obvious. If the same bedding surface is exposed on both sides of the fracture, then normal displacement is indicated (pencil for scale). **c)** Pit wall at N-32, Pine Point (Domain 3). Outlined in white are three fracture faces of varying orientations, each with dolomite slickensides indicating displacement downwards toward the pit centre (rock hammer for scale). **c (inset)** Float boulder from N-32 pit at Pine Point (Domain 3). Mineral slickensides are of dolomite (lens cap for scale). **d)** Pit wall at X-15 pit, Pine Point (Domain 3). Steeply dipping fracture that contains mineralization is labeled. Bedding-parallel mineralization is also indicated (rock hammer for scale). **d (inset)** Sulphide minerals in curving fracture (lens cap for scale). **e)** Pit wall at N-42 pit, Pine Point (Domain 3). Hydrothermal dolomite in bedding-parallel bands (zebra texture) is crosscut by systematic joints (rock hammer for scale). **f)** P-29 pit at Pine Point (Domain 3). Light-coloured rock near the top of the pit wall is pervasively dolomitized. The hydrothermally altered beds are crosscut by systematic joint sets (person for scale).*

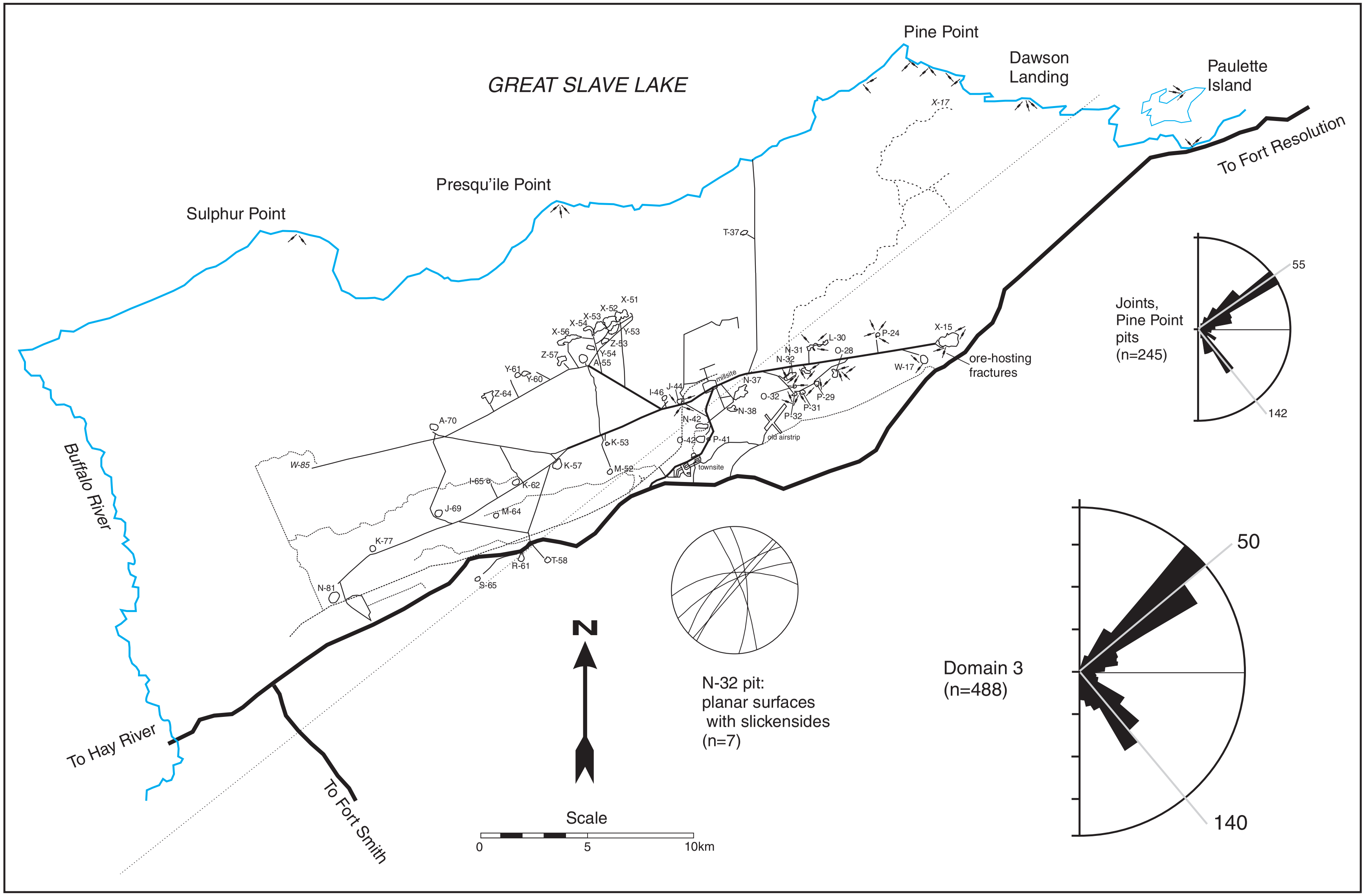


Figure 4. Pine Point mining district in Domain 3, with rose diagrams of joints for all of Domain 3 and joints measured in the easternmost pits at Pine Point. The mean orientations for the dominant joint sets are plotted adjacent to their respective pit, as well as at shoreline exposures. For simplicity, all joints are plotted as vertically dipping. Also shown is an equal-angle stereograph with great circles representing slickensided fracture surfaces measured in the N-32 pit.

Joints typically show no evidence of either displacement or fluid movement along them. Observations recorded from the four domains are discussed below.

Domain 1

In total, 512 joint surfaces were measured in Domain 1 (Fig. 2). Three preferred orientations appear to be centred at 012°, 070°, and 160°, although scatter is evident. The majority of the measurements included in this population were obtained from blasted roadcuts. As a check on the scatter, the data collected from two bedrock areas that showed no evidence of blasting were plotted on a separate rose diagram (Fig. 2). Although the data set is small (n=30), the rose diagram does resolve into two preferred directions (055° and 145°). The latter orientation is included in the population with the peak at 160°. The 070° joint set may then actually represent the averaging of northeast-southwest (approx. 055°) and east-west (approx. 090°) joint sets (Fig. 2), thus indicating the presence of four preferred orientations in Domain 1 (012°, 055°, 090°, and 160°).

A fault zone was measured at McNallie falls, 37.5 km northwest of the Enterprise junction on Highway 1 (Fig. 2). Douglas (1959) previously mapped this fault zone as a northwest-trending normal fault (northeast side down) in the Alexandra Member of the Twin Falls Formation, with a displacement of approximately 9 m. The beds at McNallie falls have an approximate orientation of 150°/20°SW. The sense of displacement of smaller faults measured at this location by the authors is in agreement with previously mapped results. Measured slip planes have a mean orientation of 340°/69°NE (Table 1). Some of the joints (typically 1–6 mm wide) of this orientation are filled with calcite, along with those oriented at approximately 150° with subvertical dips. Sparse disseminated pyrite was observed in a calcite vein of the latter orientation.

In addition to the hydrothermal calcite observed in fractures at McNallie falls, two fractures that contain coarse sparry calcite and saddle dolomite and have orientations of 327°/76°NE and 133°/88°SW were observed in a quarry located about 18.6 km northwest of Enterprise (Fig. 2). As well, a few variously oriented, thin subvertical fractures, containing hydrothermal calcite, were observed in other parts of the study area.

Domain 2

The Domain 2 rose diagram (Fig. 2) was compiled from 280 joint measurements taken along the Hay River gorge. Four joint sets are evident in Domain 2: a pronounced set at 055° and subsidiary sets at 074°, 125° and 150° (Table 1). The 055° and 150° sets in Domain 2 are consistent with those orientations observed in the Domain 1 subset.

Evidence of displacement was observed on a single fracture plane slightly upstream of Alexandra Falls (Fig. 2). Here, grooves and striations were observed on a fracture oriented at 166°/66°SW (Fig. 3b). The striations plunge 256°/66° down the fracture surface, indicating predominant dip-slip movement in the Alexandra Member limestone (Twin Falls Formation) at this location.

Downstream of Louise Falls (Hay River gorge), iron staining was observed in fractures with orientations of 160 to 170° on the cliff face (Alexandra Member of the Twin Falls Formation; Fig. 2). Talus boulders, found near the base of the cliff, have calcite and iron-sulphide coatings on fracture surfaces.

Domain 3

Joint measurements collected from Domain 3 are represented by the rose diagrams shown in Figures 2 and 4. This domain includes 488 joint measurements that were compiled from the Pine Point minesite, as well as from the shoreline of Great Slave Lake and roadside outcrop. Dominant joint sets were observed at 050° and 140°, consistent with observations in domains 1 and 2 (Table 1).

Local displacement was evident at one locality within the N-32 pit at Pine Point, characterized by dolomite slickensides along the fractured surfaces of dolostone blocks (Fig. 3c, 4). There is no systematic orientation to the fracture surfaces, but the slickensides in all cases indicate slip toward the pit centre.

With very few exceptions, sulphide mineralization is absent in systematic joints in the open pits. Exceptions, however, do exist in the X-15 pit, where two fractures were observed to contain hydrothermal dolomite and ore minerals. The first fracture, oriented at 194°/83°NW (Fig. 3d), is rather irregular, with slight jogs at bedding surfaces, and appears to pinch out with depth. The second fracture, which occurs

Table 1. The dominant fracture orientations as determined for the four geographic domains in relation to the Great Slave Lake Shear Zone and inferred Hay River Fault Zone. Other significant faults are tabulated.

Domain	Dominant joint set orientations	Known and inferred major structures
1	012°, 055°, 090°, ~160°	McNallie Fault (~340°) Hay River Fault (~055°)
2	055°, 074°, 125°, 150°	
3	050°, 140°	Great Slave Lake Shear Zone–McDonald Fault (~045°)
4	057°, 104°, 157°	Bell Rock Fault (~020°)

within metres of the first, curves from 253°/78°NW at the lower levels to 219°/80°NW higher up the pit wall (Fig. 3d, inset).

Typically, the main observation in Pine Point pits was that the hydrothermal dolomite commonly associated with ore minerals was fractured by late-stage joint sets (Fig. 3e, f). This observation is direct evidence that the joints formed after hydrothermal dolomite and ore emplacement.

Domain 4

Domain 4 is composed of 25 measurements compiled from the Bell Rock and Little Buffalo River falls outcrops (Fig. 2). This rose diagram shows three dominant joint orientations, at approximately 057°, 104°, and 167° (Table 1).

A fault zone was examined at Bell Rock, just off Highway 5 near Fort Smith (Fig. 2). Bell Rock has been previously documented by Camsell (1917), Cameron (1922), Douglas (1959), and Norris (1965), among others. The outcrop is composed of gypsum interbedded with shale of the Chinchaga Formation, in faulted contact with brecciated limestone. Douglas (1959) mapped the fault at approximately 020° with a near vertical dip. Individual slip planes measured by the authors yielded a mean of 021°/70°SE (n=5), which is in good agreement with previous mapping (Table 1; Fig. 2). Norris (1965) estimated a minimum vertical displacement of approximately 4 m (east side down). This agrees with our observation of sense of displacement from calcite slickensides on fractures. In addition, calcite-filled fractures with a mean dip of 095°/73°SW (n=5) were observed. These bore no indications of slip and were likely filled after faulting.

DISCUSSION

Comparison of fractures in southern Northwest Territories to those in Alberta

The regional structural study shows that there is relative consistency of the fracture orientations in the southern Northwest Territories. The northeast-southwest (approx. 055°) set is observed in all four domains, whereas the east-west (approx. 80–90°) set is only found in Domain 1. The northwest-southeast fracture set is also present in all four domains, but varies from 160 to 165° in domains 1 and 4, and to 140° in Domain 3, and displays two orientations (125°, 150°) in Domain 2.

The presence of northeast-southwest and northwest-southeast joint sets (termed ‘System I’ by Babcock, 1973) was also documented in central Alberta, and to a lesser extent in northeastern Alberta, in the McMurray and Waterways formations (Babcock 1974, 1975; Pana, 2002). Babcock (1973) attributed the orientation of these joint sets to extensional fracturing that occurred normal and parallel to the Rocky Mountains as a result of Laramide orogenic stresses. Babcock (1975) and Pana (2002) mentioned, however, that the abundance of joints with these orientations is reduced further north in Alberta, which they attributed to a reduction of stress with increasing distance from the Laramide fold-and-thrust belt. If this is the case, it is unlikely that the effects of Laramide orogenesis would be pronounced in the study area. Therefore, there may an alternate cause for the orientations of these northeast-southwest and northwest-southeast joint sets.

Relationship between fractures and major regional basement structures

In addressing the significance of these dominant northeast-southwest (055°) and northwest-southeast (145°) joint sets, it is necessary to look for other mechanisms that may have caused the fracturing. One possible explanation is tectonic reactivation or propagation upward from existing faults in the underlying basement. Such structures include the Great Slave Lake Shear Zone, which is bounded by the McDonald and Preble faults (Douglas, 1959), as well as the Hay River Fault Zone.

The Great Slave Lake Shear Zone and its associated bounding faults have an approximate orientation of 045° in the Pine Point mining district (Douglas, 1959). This orientation is approximately 5 to 10° off that determined for the dominant joint set in the Pine Point area (Domain 3; Fig. 4). As well, the Hay River Fault Zone, a basement fault that is inferred to underlie the stratigraphy west of Hay River (Williams, 1990; Burwash et al., 1994), has an orientation of 055°, consistent with the orientation of the northeast-southwest joint set observed in Domain 1. This being said, the two Phanerozoic faulted outcrops observed in domains 1 and 4 (McNallie falls and Bell Rock, respectively) had orientations of approximately 340° and 020°, very different from those of the inferred Precambrian fault zones.

Relationship between joint sets and Pine Point mineralization

It has been previously proposed that the McDonald Fault (the southeastern bounding fault of the Great Slave Lake Shear Zone) may have acted as a conduit for ore-bearing fluids in the Pine Point ore district (Campbell, 1966). The fact that no large-scale fault zones or obvious major structural breaks were observed in the accessible pits at Pine Point does not support this proposal. Nevertheless, a few examples were observed in the N-32 and X-15 pits that support active structural influences at the time of deposit formation. In the N-32 pit, dolomite slickensides on faulted dolostone blocks are interpreted to have occurred at a local scale, caused by block slumping that occurred at the edge of a sinkhole as a result of subsurface karsting. In the X-15 pit, two joints containing ore minerals were observed; however, one of the joints pinches out within a few metres, and was unlikely to have served as a major fluid conduit.

Aside from these two isolated occurrences, observations of the joints in the open pits at Pine Point indicate that they host no mineralization. It is therefore difficult to make a case for the orientation of the joint sets or any observable structures being associated with ore deposition in the Pine Point mining district. Further, Precambrian fault reactivation as a pathway for mineralizing fluids is not supported by the 065°

orientation (Rhodes et al., 1984) of the Pine Point ore trends, which diverge from the orientation of the Great Slave Lake Shear Zone by about 15°.

Previous work by Krebs and Macqueen (1984) and Rhodes et al. (1984), among others, has documented a paragenetic relationship in which select phases of coarse hydrothermal dolomite are coeval with the ore minerals in the Pine Point mining camp. As this study has determined that joint sets typically crosscut hydrothermal dolomite layers commonly containing ore minerals, there is direct evidence for joints forming subsequent to hydrothermal dolomite and ore emplacement.

CONCLUSIONS

1. Regionally consistent northeast-southwest (055°) and northwest-southeast (typically 145–165°) joint orientations are evident throughout the study area south of Great Slave Lake. These regional joint orientations are also observed in northern and central Alberta, and one set (055°) is subparallel to the Great Slave Lake Shear Zone and the Hay River Fault Zone. No evidence of shear or slippage was observed in the joints with these northeast-southwest and northwest-southeast orientations. The few instances of slip observed are in other orientations and are correlated with known Phanerozoic fault zones, or are presumed to be a result of local collapse at the edge of karst features.
2. These same regional joint orientations were observed in the open pits at Pine Point; however, no ore mineralization appears to be associated with these joint sets. Furthermore, joints of these orientations crosscut the bedding-parallel, hydrothermally dolomitized zones. As the observed dolomite layers commonly host the ore minerals, the fractures are interpreted to be unrelated to mineralization. No fault zones were observed in the Pine Point pits, nor any major structures that could be inferred to control mineralizing conduits. Therefore, an overriding structural control on the deposition of ore mineralization in the Pine Point mining camp is not supported by this study.

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