EUB/AGS Geo-Note 2002-15

Structural Control of Lead-Zinc Mineralization In Carbonate Sequences of Northern, Alberta: A Contribution to the Carbonate-Hosted Pb-Zn (MVT) Targeted Geoscience Initiative

Alberta Energy and Utilities Board
Alberta Geological Survey

EUB/AGS Geo-Note 2002-15

Structural Control of Lead-Zinc Mineralization In Carbonate Sequences Of Northern Alberta: A Contribution to the Carbonate-Hosted Pb-Zn (MVT) Targeted Geoscience Initiative

D.I. Pana

Alberta Geological Survey

August 2003

When using information from this publication in other publications or presentations, due acknowledgment should be given to the Alberta Geological Survey/Alberta Energy and Utilities Board. The following reference format is recommended:

Pana, D. I. (2003): Structural control of lead-zinc mineralization in carbonate sequences of northern Alberta: a contribution to the carbonate-hosted Pb-Zn (MVT) Targeted Geoscience Initiative; Alberta Energy and Utilities Board, EUB/AGS, Geo-Note 2002-15.

Published August, 2003 by:
Alberta Energy and Utilities Board
Alberta Geological Survey
4th Floor, Twin Atria Building
4999 – 98th Avenue
Edmonton, Alberta
T6B 2X3

Telephone: (780) 422-3767 (Information Sales)
Fax: (780) 422-1918
E-Mail: EUB.AGS-Infosales@gov.ab.ca

Web Site: www.ags.gov.ab.ca

Cover Photo: Typical rectangular blocks defined by bedding/joints intersection in carbonate strata of the Middle Devonian Waterways Formation, Athabasca River, west of Fort McMurray

Contents

Figures

Acknowledgements

The author acknowledges reviews of the initial manuscript by R.A. Olson and R.J. Rice which have improved the final version of this Geo-Note.

Abstract

Field investigations of the Devonian carbonate stratigraphy and deformation pattern in the Interior Plains of northern Alberta, corroborated with existing data on MVT deposits and prospects in the Rocky Mountains fold-and-thrust belt and on the Pine Point MVT district, indicate that the MVT mineralization in carbonate sequences of the Western Canada Sedimentary Basin is epigenetic. All MVT occurrences are confined to a halo of late hydrothermal dolomitization invariably related to fractures or fault zones. Hydrothermal ore fluids were hotter than what could be reasonably obtained from burial or advecting basin fluids. Consequently, huge volumes of highly saline fluids invoked by basinal fluid flow genetic models are not critical factors for the MVT mineralization. Tectonically induced, secondary porosity of carbonate rocks appears to be the main trap for ore-bearing fluids. The occurrence of highly porous reefs is a favourable geologic feature for the development of MVT, but is not a critical factor.

Cambrian and Devonian platformal carbonate sequences of the WCSB that developed on the ancestral passive margin of North America are the primary hosts of MVT deposits and prospects. For the portion of the WCSB carbonate stratigraphy involved in Mesozoic orogenies, routinely invoked basinal fluid flow models for MVT deposits are irrelevant. MVT deposits and prospects in the Rocky Mountains fold-and-thrust belt appear to be related to the Laramide orogeny and/or to post-orogenic collapse.

The MVT mineralization in Paleozoic carbonate sequences involved in the Mesozoic foreland basin is related to zones of recurrent strain in the Precambrian basement. Pine Point district is structurally controlled from continental to deposit scale. It is located along the transcrustal Great Slave Lake Shear Zone with the individual deposits within the district distributed in linear trends above basement fault scarps. Saline water from successive basins may have repeatedly infiltrated a recurrent fault zone, extracted and transported metals in an open system, low- to medium-grade metamorphic environment; focussed within linear zones of strained/permeable basement; finally, the metal-bearing waters were released and reacted with the carbonate caps at the site of ore deposition, from prospect or mine to district scale. The likely driving forces for fluid flow may have been a combination of topography, thermal convection and hydraulic pumping.

Based on the inferred genetic relationships between zones of recurrent strain in the basement and overlying carbonate stratigraphy, several exploration target areas for MVT are identified in northeastern Alberta.

1 Introduction

The Alberta Geological Survey is involved in a two-year federal-provincial Targeted Geoscience Initiative (TGI) on Mississippi Valley Type (MVT) lead-zinc deposits in the Western Canada Sedimentary Basin (WCSB). Good exploration strategy is based on appropriate criteria for exploration area selection, and correctly assessing the relative importance of these criteria. It is the second aspect of exploration strategy that is the main concern of this paper.

Paleozoic carbonate lithologies of the WCSB deposited on the western passive margin of ancestral North America crop out in two major Mesozoic tectonic settings: 1) the Interior Plains of northeastern Alberta as part of the foreland basin; and 2) in the Rocky Mountains involved in a fold-and-thrust belt. This Geo-Note includes structural observations collected in the Interior Plains of northern Alberta. Much of the carbonate sequence in the Interior Plains is inaccessible, with wetlands and glacial cover, which render surface exploration difficult and expensive. The only outcrops are along major rivers in northern Alberta. During the summer of 2001, AGS conducted exploration along the Athabasca, Clearwater and Peace rivers. Samples for petrographical and chemical analysis have been collected from various carbonate horizons and the assay results are reported in Eccles and Pana (2003). More than 800 planar structural features have been measured at about 70 stations in the Waterways Formation and included in the AGS's Bedrock database constructed for the MVT project. Station numbers referred to in this report are consistent with this database. Information from the database has been collected into a GIS summary of field data (Waters and Rice, 2003). A summary of year one achievements for the AGS's MVT project is provided in Rice (2003). Field examination of the Middle Devonian Waterways Formation along the Athabasca and Clearwater rivers in the Fort McMurray area and of the Upper Devonian Mikkwa and Grosmont formations along Peace River and Harper Creek in the Vermilion Chutes area (Figure 1) is part of a more comprehensive study of deformation recorded by carbonate sequences in northern Alberta. In addition to outcrop examination of the nature and geometry of structural elements this study includes examination of the nature of fractures in cores, geophysical logging, and remote sensing techniques, which will be completed in the coming year.

Our field observations corroborated with a preliminary review of published information indicate that all carbonate hosted lead-zinc occurrences in the WCSB are strictly related to 'fault zone processes'. We suggest that basement fractures identification may be an effective exploration tool for MVT in the Cordilleran foreland of Alberta. The following notes represent a first step towards a comprehensive re-evaluation of the MVT genetic model in an attempt to improve and focus exploration programs.

2 Previous Work

Hand specimens with lead-zinc mineralization, reportedly from the Wood Buffalo National Park, sparked the interest of the Alberta Research Council that led to a geochemical survey by Govett in the late 1950s. Green (1971) undertook a reconnaissance scale geochemical exploration survey over a substantial area of northeastern Alberta, which included a large part of Wood Buffalo National Park, north of Peace River. Low-level zinc anomalies were found in Cretaceous shale outcrops, but in general, lead-zinc concentrations were not encouraging. Carrigy (1959) reported a galena occurrence at Whitemud Falls on Clearwater River in dolostone of the Methy Formation which he correlated with the Presqu'ile Formation dolomite, but noted "sulphides are not widespread in occurrence". Haites (1960) published a list of sphalerite occurrences in three wells in the Leduc Formation carbonates of the Duhamel Field, including some "ore grade" sections between approx. 1500-1600 m depth. He noted that sphalerite was also found in most wells of the Norway and Malmo fields on the same reef trend as the Duhamel field, and advocated for fracture control for both reef development and mineralization. Sphalerite was also reported in the Bonnie Glen and Wizard Lake fields where vertical fractures are well

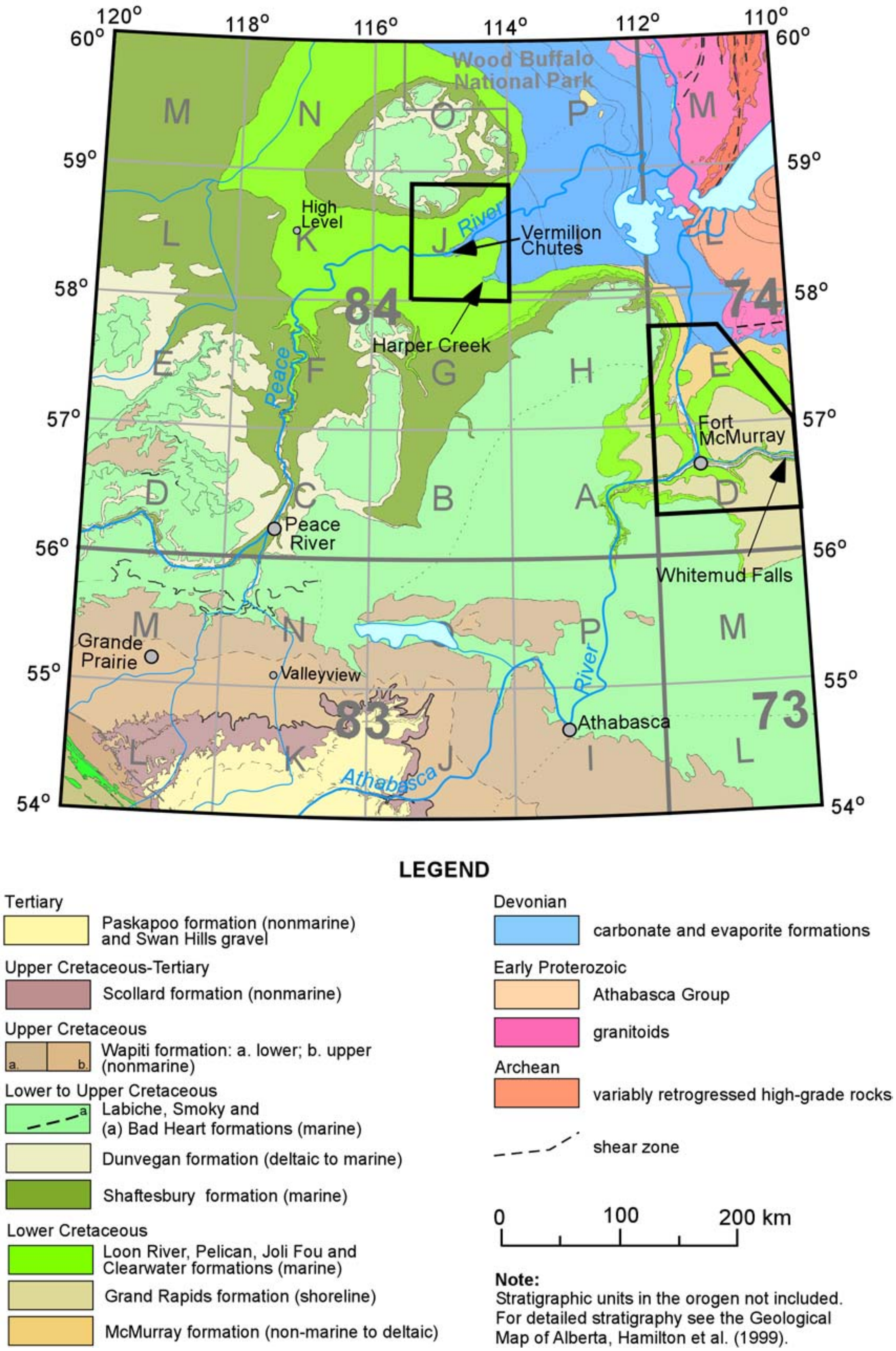

Figure 1. Geological map of Alberta with locations of the areas examined for potential Mississippi Valley type deposits.

documented (Haites, 1960). A copper anomaly in the Paleozoic cover was found at Stony Islands on the Slave River north of Fort Chipewyan and related to a secondary copper occurrence in the basement regolith (Godfrey, 1973).

Gulf Minerals Ltd. (1975) reported a minor zinc anomaly of 0.1% at Vermilion Chutes on the Peace River. Devonian reef facies carbonates onlapping the Athabasca Sandstone near the erosional edge in northeastern Alberta were considered very similar to the carbonate sequence at Pine Point and therefore favourable for lead-zinc occurrences (Walker, 1981). Diamond drilling to test deep uranium targets in the Athabasca Basin in Alberta intersected disseminated galena-sphalerite associated with a 100 m wide fracture zone in sandstone at a depth of about 500 m (Nelson, 1970). Dubord, (1987) provided a list of 18 mineralized wells in northern Alberta, and Turner and McPhee (1994) studied the potential for Pb-Zn mineralization and reported assay results on core samples from northern Alberta. The only significant Zn concentrations of up to 10 % were reported from a carbonate breccia above the Great Slave Shear Zone at 1285 m depth.

In northeastern Alberta, Devonian carbonates onlap the Precambrian crystalline basement and the non-metamorphosed Precambrian clastics of the Athabasca Group (Figure 1). The carbonate bedrock in this region has been extensively eroded and now occupies low ground, hence much of the potential outcrop area is hidden by wetlands and glacial cover. Inliers of these Devonian carbonates are found near Fort McMurray along the Athabasca and Clearwater River valleys, in the floor of the oil sands open pit excavations, and in two outcrops stretching more than 2 km each along Peace and Harper rivers.

3 Structural Elements In Northeastern Alberta (Fort McMurray Area)

The investigated area is located in northeastern Alberta within NTS 1:250 000 scale map sheets 74D (Waterways) and 74E (Bitumount) near the town of Fort McMurray (Figure 1). Outcrops of carbonate rocks are exclusively the Waterways Formation, the uppermost stratigraphic unit of the west-dipping Devonian carbonate / evaporite succession. Devonian rocks unconformably overlay the Precambrian crystalline basement and to a lesser extent non-metamorphosed rocks of the Early Proterozoic Athabasca Group. Oil sands of the middle Albian McMurray Formation overlap progressively older Devonian rocks eastward. Outcrops are largely restricted to the valleys of the Athabasca and Clearwater rivers and a few of their tributaries, and lie near water level. Examined outcrops include

- all carbonate outcrops on Athabasca River from Cascade Rapids downstream to about 100 km north of Fort McKay;
- all outcrops on Clearwater River up to Cascade Rapids, three more outcrops at and immediately upstream of Whitemud Falls as well as the basement/cover contact in Saskatchewan; and
- outcrops on lower Christina River.

3.1 Bedding

Bedding is gently flexed into apparent wide-open folds with amplitudes of 15-30 m and wave-lengths of 100 m to 1/2 km (Figure 2). At least some of these apparent folds may be sections through dome structures formed in response to differential subsidence related to salt dissolution and volume changes accompanying hydration of evaporates in the underlying Prairie Evaporite Formation.

Figure 2. Open folds in carbonate strata of the Middle Devonian Waterways Formation along the Athabasca River, near Fort McMurray. Station RR01-74E-53. Bedding orientation on east-west and north-south transects along the Athabasca River suggest low amplitude domal structures; a) west dipping strata along the east-west segment of the Athabasca River, west of Fort McMurray; b) north and south dipping strata along the north-south segment of the Athabasca River, north of Fort McMurray.

3.2 Joints

An attempt was made to collect data at enough locations to allow definition of regional patterns of joints, if present, or to determine if areal variations in the patterns occur. Where possible, for each joint the following features were collected: strike, dip, spacing to next joint of the same set, length along strike and vertical continuity.

The number of outcrops at which numerous joints could be measured was limited, but at most stations at least 15 joint orientations were measured. Outcrops of the Waterways Formation form low scarps up to a kilometre long and usually less than 3 m high, and generally extend at the most 3 m back from the scarp face (Figure 3). Consequently, length along strike for joints that are not parallel/subparallel to the scarp face was not measurable. Similarly, because most joints extend vertically and horizontally beyond the limits of outcrop, it was usually not possible to obtain an accurate measurement of their length in the dip direction (vertical continuity).

Where the rock is of a single lithology the joints usually cut vertically through the entire 2-3 m exposed outcrop (Figure 4). However, jointing of alternating resistant and recessive units is un-homogeneous: in more resistant beds of microcrystalline limestone the joints are more closely spaced ranging from 5 to 150 cm, whilst spacing in the friable shaly limestone beds is in the range of 10-200 cm. Commonly, joints in more resistant limestone beds terminate at the contact with more recessive friable lithology (Figure 5). The strike of joints in the relatively competent microcrystalline limestone beds and adjacent shaly limestone is usually the same.

Joints in the Waterways Formation dip normal to bedding, which dips less than 10° (Figure 2). The general vertical dip of the joints (within the error of measurement) prevents three-dimensional analysis and consequently, a two-dimensional directional analysis was carried out.

Four joint sets are present which make up two orthogonal systems: a north-south and east-west system and a northeast-southwest and northwest-southeast system. No single set of either orthogonal system is consistently cross cutting. At one outcrop the north-south set may comprise the systematic set, whereas at the adjacent outcrop it will be the truncated set. At some locations it was not possible to determine which sets are crosscutting, if any.

Typically, two orthogonal joint sets are present at most outcrops that break the Waterways Formation limestone into rectangular blocks in plan view (Figure 6). The sets are defined by a close grouping of joint strikes, and very few joints at a given location have strikes differing greatly from the set means. The preference of the strikes is so strongly pronounced that statistical tests are generally unnecessary to separate the sets (Figure 6). However, at several locations joint orientation shows a wide range and their inclusion into one of the four dominant sets appears tenuous. There is clear evidence that some joints are younger than the post Albian hydrocarbon migration into the McMurray sandstones (Figure 7).

The four joint sets observed in the Fort McMurray area correspond to joint systems mapped elsewhere on the Alberta plains: the first joint system sets striking roughly parallel and normal to the trend of the Rocky Mountain Front Ranges, and the second joint system sets striking approximately north-south and east-west (System I and II, respectively as defined by Babcock 1973, 1974 and 1975). Joint system I is strongly developed close to the Rocky Mountains where it is present at most outcrops and may be caused by Laramide orogenic stresses (Babcock, 1973). The rarity of outcrops with system I dominant in the McMurray area would reflect the decrease in stresses strength 600 km away from the Laramide fold-

Figure 3. The Devonian / Cretaceous unconformity exposed along the Athabasca River, west of Fort McMurray. Station RE01-74D-25. Devonian carbonate outcrops, although hundreds of metres long, may display only limited or no significant structural information.

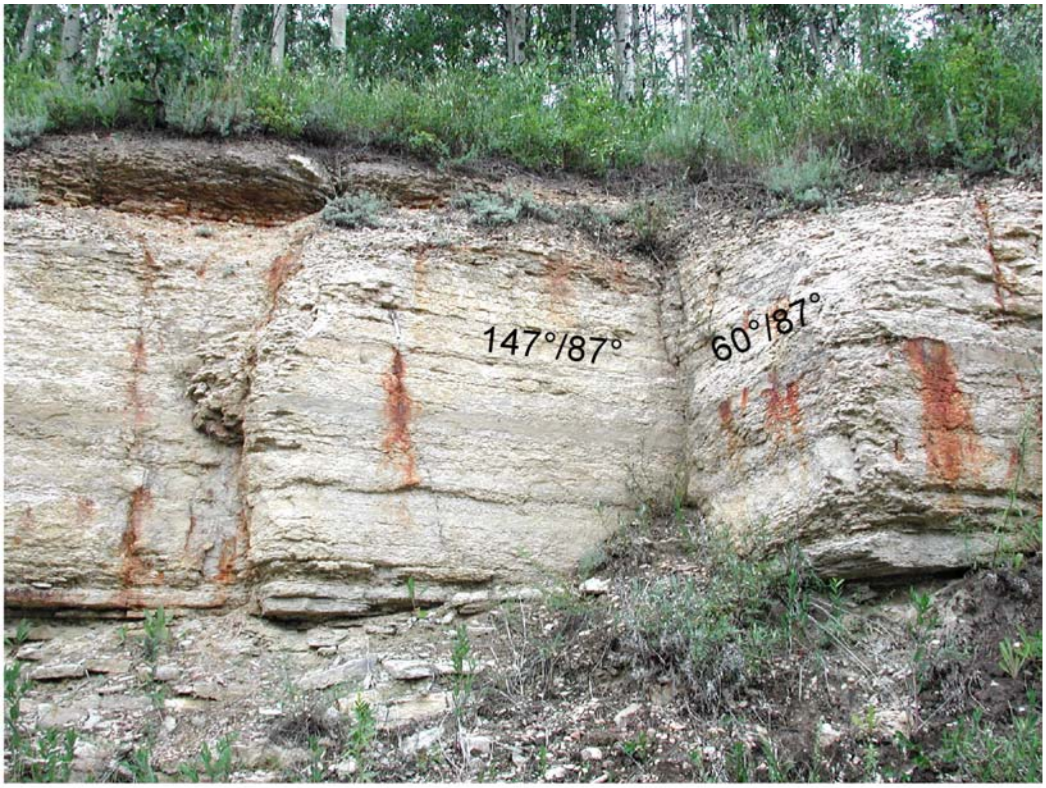

Figure 4. Orthogonal joint system within a homogeneous stratigraphic unit of the Waterways Formation. Station RR01-74D-34. The joint system is well expressed and consistently oriented within a two metres thick stratigraphic unit of the Waterways Formation, north side of Athabasca River.

Figure 5. Rheology–dependant orientation of joints in carbonate strata of the Waterways Formation. Station RE01-74D-24. Vertical northerly trending joints in the middle thick bedded stratigraphic unit B correspond to a joint system in the underlying massive unit A and disappear in the overlying thinly bedded, rubbly unit C.

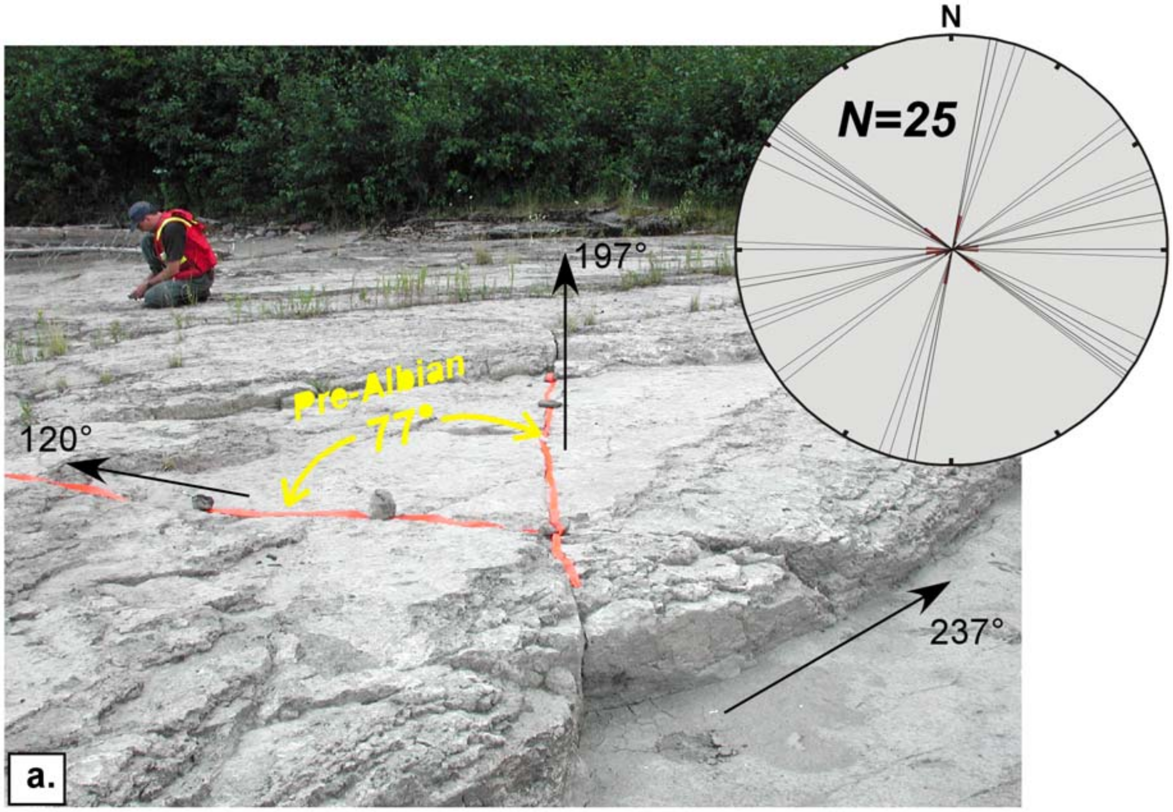

Figure 6. Joints orientation patterns in carbonate strata of the Middle Devonian Waterways Formation west of Fort McMurray. Station RE01-74D-29. a) One joint set of System I, roughly normal to the trend of the Laramide tectonic front and two 'orthogonal'sets defining System II, trending northerly and easterly. Station RR01-74D-33. b) Typical 'rectangular blocks' defined by bedding /joints intersection.

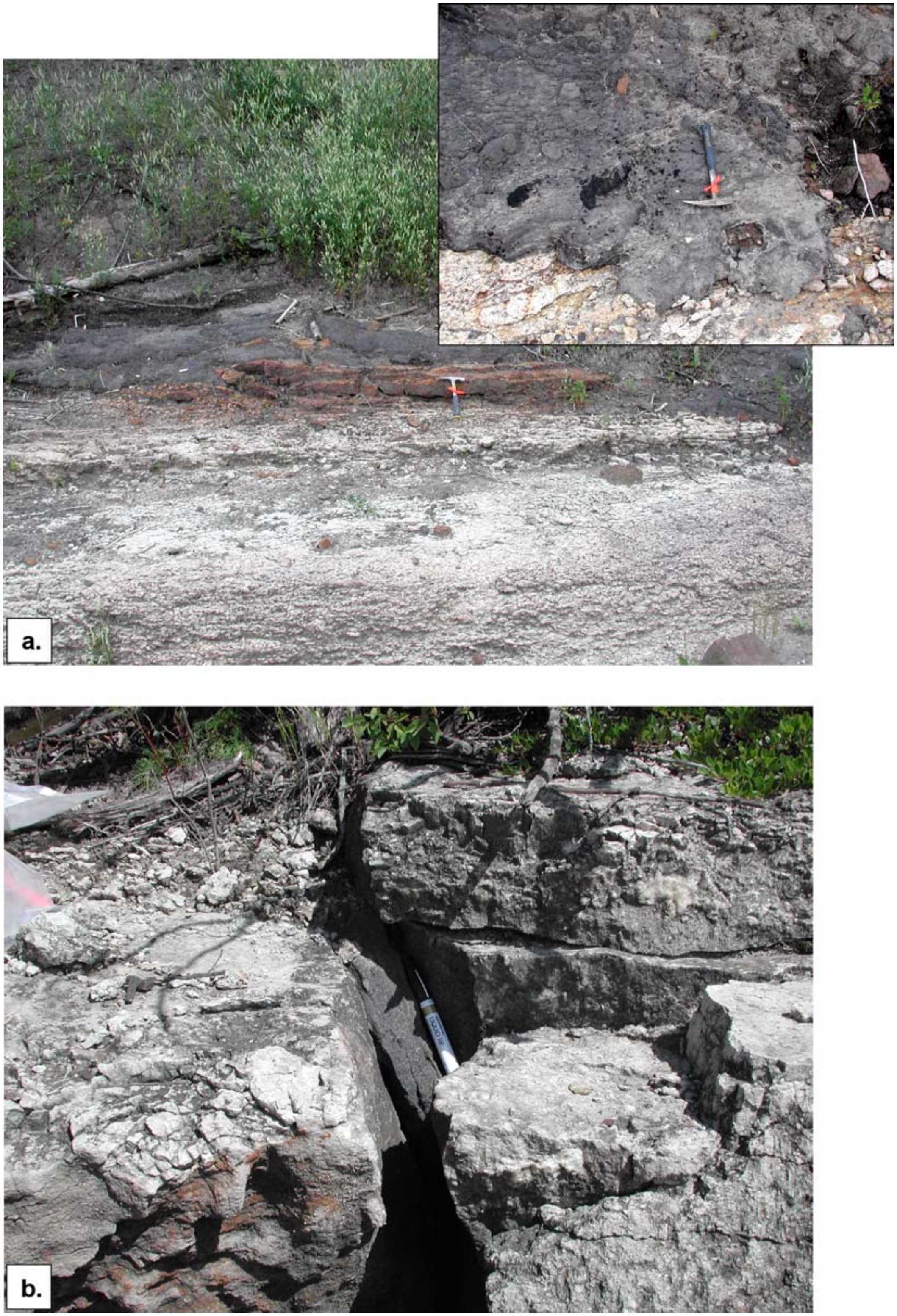

Figure 7. Time constraints on some part of the joints overprinting Devonian carbonates of the Waterways Formation. Station RE01-74D-27. a) Recent gravitational creep of the Athabasca oil sands, south side of the Athabasca River, west of Fort McMurray; Station RR01-74D-57. b) Late joints in carbonates postdate the impregnation of the Lower Cretaceous sandstone with hydrocarbons, east bank of Thabasca River, north of Fort McMurray.

and-thrust belt. The fact that joint sets in the Waterways Formation of the McMurray area are parallel to sets mapped over a large area elsewhere in Alberta strongly suggests that these are regional tectonically induced joints, and are not caused by local dissolution-induced flexures.

The north-south and east-west joint sets of the Waterways Formation do not exist in the McMurray Formation sandstone (Babcock, 1975; Babcock and Sheldon, 1976). This may indicate that the northerly and easterly trending joint sets formed prior to Early Cretaceous.

3.3 Faults

A fault zone approximately 100 m wide crosses the Clearwater River at Whitemud Falls and projects west northwestward into a straight segment of the river (Figure 8). Vertical fracture cleavages and fault planes trend between 110° and 140° (Figures 8 and 9).

Several lines of evidence suggest a possible fault zone in a large, partly covered outcrop in the eastern bank of the Athabasca River approximately 20 km north of Fort McMurray. A relatively steep downwarping of the carbonate strata is accompanied by intense jointing and overlain by unusually intense alteration in the overlying the Athabasca oilsands with at least three limonitic horizons and "clean" white-grey sandstone layers from which the heavy oil appears to have been leached out (Figure 10). Penetrative secondary planar structures of uncertain nature overprint black, hydrocarbon rich sands toward the top of the outcrop (Figure 10). They may represent either a set of closely spaced joints or fracture cleavages. Similar surfaces of discontinuity are common all along the steep southern bank of the Athabasca River a few kilometres west of the bridge in Fort McMurray. There, spectacular discontinuities in the oilsands appear as metres to tens of square metres surfaces sub-parallel to the Athabasca thalweg and represent discrete, minor scale down dip fracture cleavages related to isostatic rebound following mass unloading along the river. At the location in Figure 10, the penetrative discontinuities are almost normal to the Athabasca River and subparallel to its east trending tributary, which suggests a tectonic nature of the cleavages that may have favored erosion and location of the creek.

Occasionally, minor normal faults have been noticed in carbonates of the Waterway Formation (Figure 11).

Approximately 5 km north of Fort McMurray, a carbonate section in the eastern bank of the Athabasca River includes a metre scale discontinuity with thrust fault geometry (Figure 12). A local thrust is not precluded, but the interpretation should be taken cautiously as it is not corroborated with any other information on post Devonian compressional tectonic regime in the region. This locale is within the salt dissolution linear zone that accompanies the eastern edge of the WCSB, with frequent dome structures resulted from selective dissolution of evaporites (Hamilton et al., 1999). Consequently, it appears more prudent to view this apparent thrust as the result of oblique slip of the top portion of a dome structure along a normal detachment.

3.4 Inferred Faults in Sub-Surface

At several stations, a close parallelism exists between the northerly course of the Athabasca River and the north-striking joint set. The straightness of several valley segments suggests that they may be structurally controlled, possibly joint-controlled.

At least some of the northerly trending vertical discontinuities examined along the Athabasca River west

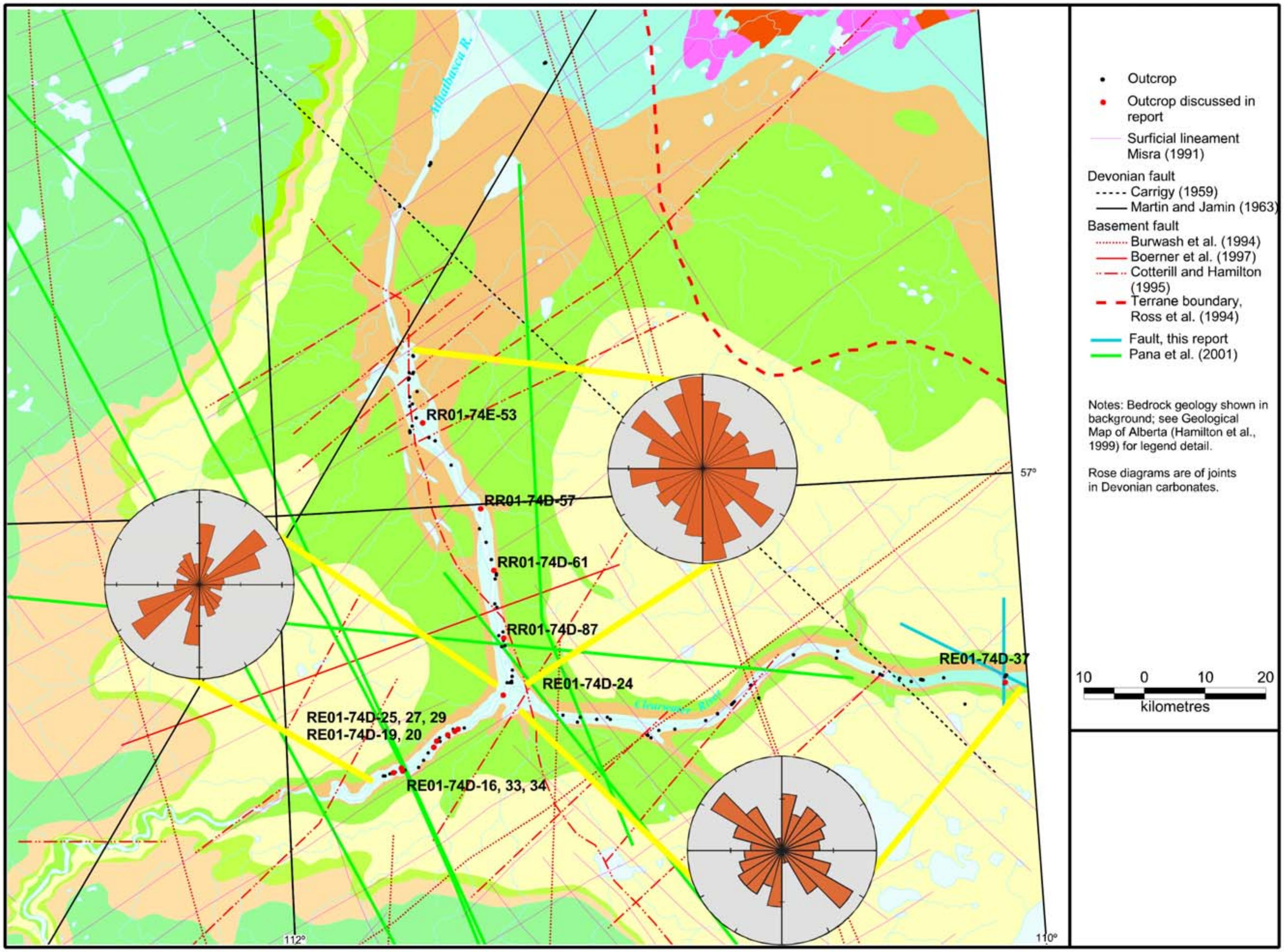

Figure 8. Known and inferred fractures in northeastern Alberta, Fort McMurray study area (from Pana et al., 2001).

Figure 9. Normal slip fault zone within carbonate strata of the Methy Formation at Whitemud Falls, Clearwater River. Station RE01-74D-37. Discrete fault planes spaced at 10 to 50 cm have minor offset and variable dip; a) west bank, fault orientation 200°/87°; b)east bank, fault zone orientation 35°/80° (orientations as dip direction/dip).

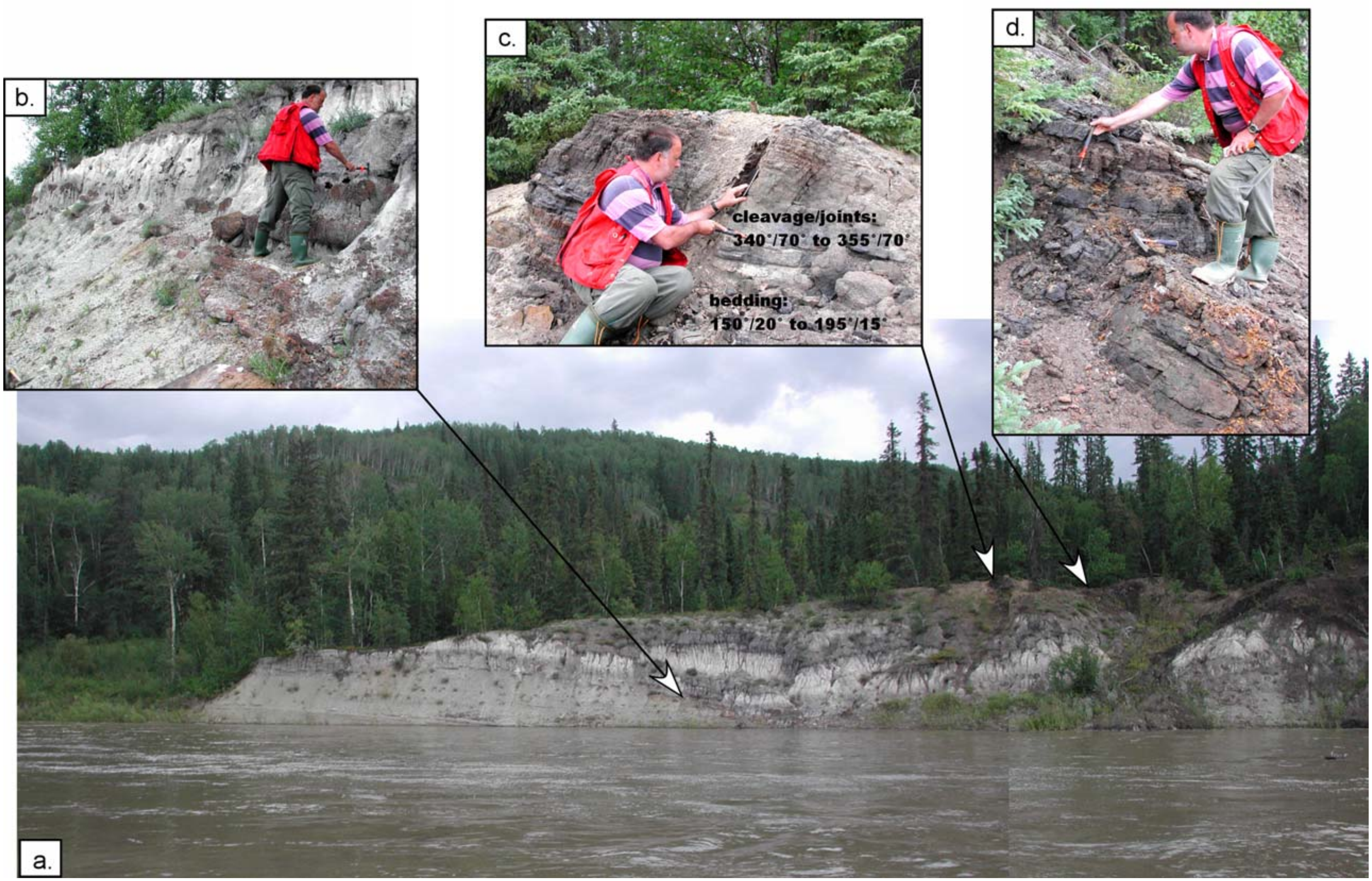

Figure 10. Inferred fault zone overprinting carbonates of the Middle Devonian Waterways Formation and oil sands of the Albian McMurray Formation. Station RR01-74D-61. a) general view of the eastern bank of Athabasca River (approximately 10 km north of Fort McMurray,; bedding flexure and jointing in carbonate strata at the base of outcrop; b)limonitic alteration at several horizons within the overlaying Athabasca oil sands, alternate with argillaceous non-bituminous ("clean") sands; c) penetrative cleavage in the oil sands appears associated with more intense limonitic alteration; d) alteration intensity increases towards the trogh to the right of photograph. Penetrative joint/cleavages in the oil sands are subparallel to Wood Creek behind the outcrop (orientations as dip direction/dip).

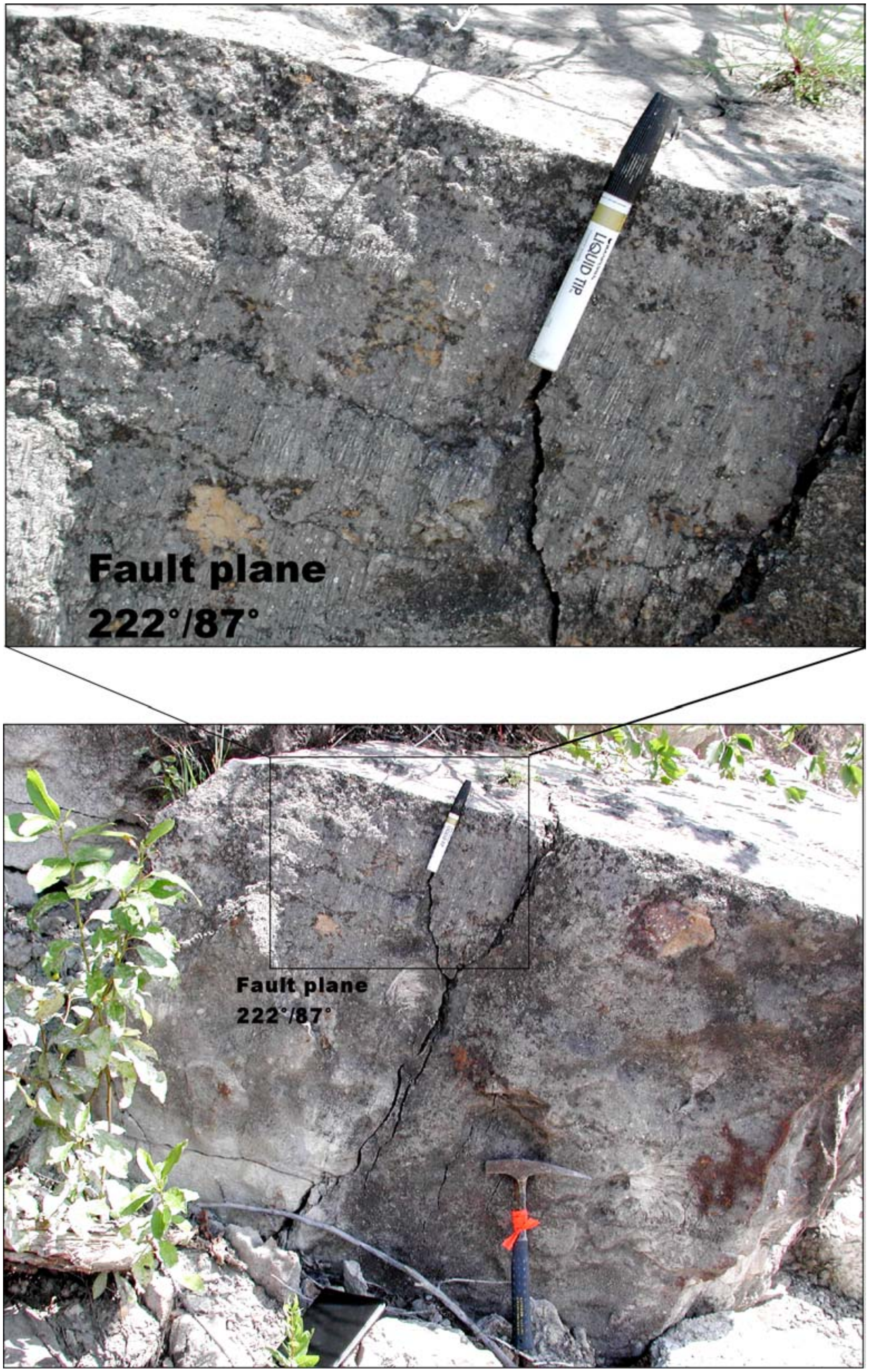

Figure 11. Minor normal fault in fossiliferous carbonate strata of the Waterways Formation. Station RR01-74D-57. East bank of Athabasca River, approximately 400 m south of Suncor bridge; bedding orientation varies from 246°/15° to 282°/5°; note steeply plunging striations and steps in the footwall.

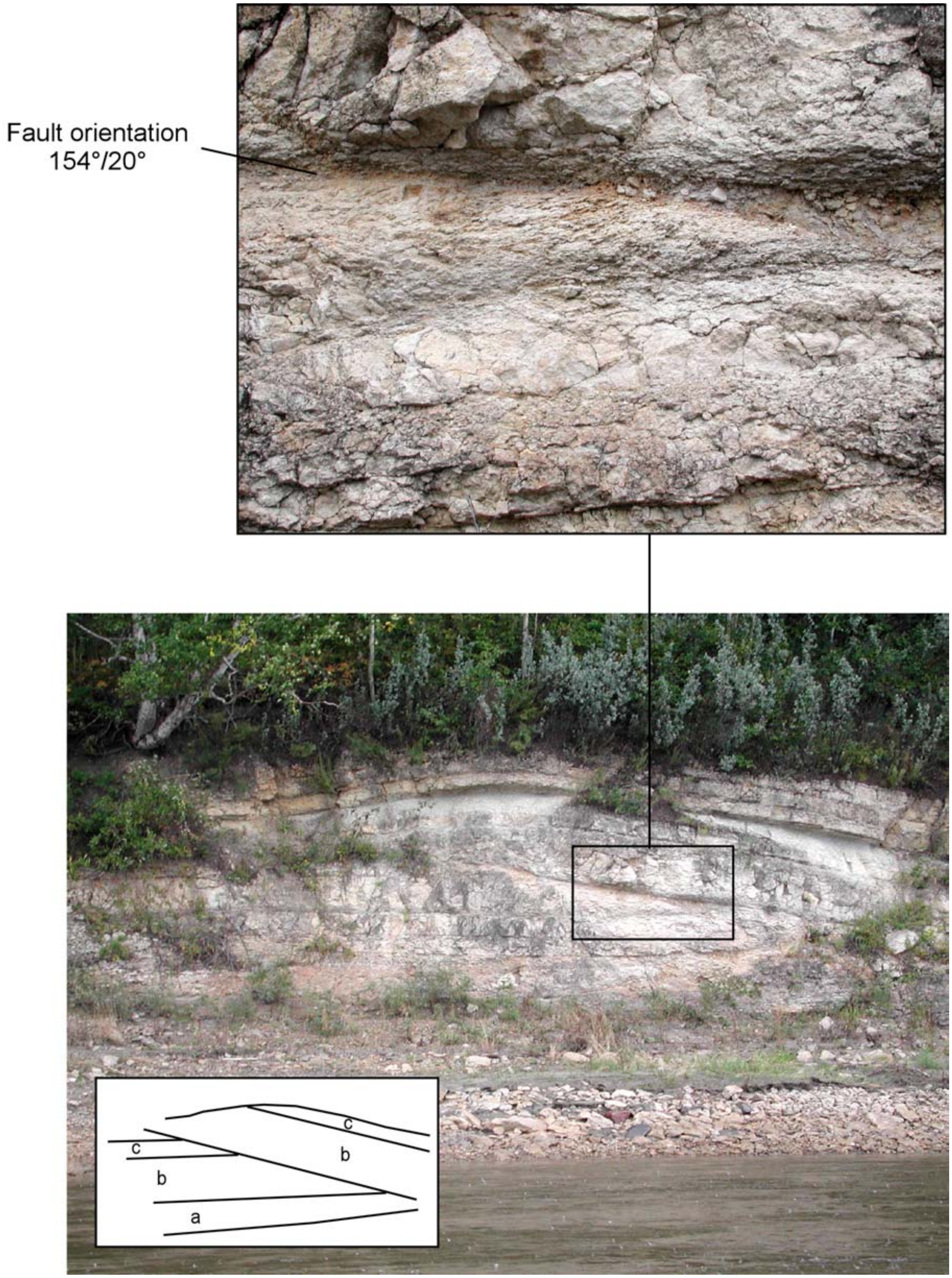

Figure 12. Thrust fault geometry in carbonates of the Waterways Formation, east side of Athabasca River, approximately 5 km north of Fort McMurray. Station RR01-74D-87. This geometry may have resulted from oblique slip of b and c beds in the hanging wall along a normal detachment from a dome apex.

of Fort McMurray (see next section) may be faults with the shear fabric obliterated by ascending post-tectonic low temperature hydrothermal fluids. Warm basinal fluids discharged in this area or basement fluids ascending along deep-seated faults may have dissolved and stained the carbonate wall-rock (Figures 13 to 15). Because the exposed stratigraphy does not record any significant vertical offset, faults interpreted in this area (Figure 8) are constrained to very minor and almost exclusively strike-parallel post-Devonian displacement.

Worth noticing is that the north-trending joint/fracture direction associated with the alteration of the limestone along the Athabasca River west of Fort McMurray parallels the general grain of the basement (trend of inferred lithotectonic assemblages and/or structures), as depicted by aeromagnetic data. The role of basement structures in producing joint patterns in the Waterways Formation in the McMurray area was discussed by Coterill and Hamilton (1995), but a direct relationship remains elusive. HRAM coupled with more field observations may help understand the role of basement structures in the development of faults in the sedimentary cover.

4 Structural Elements in Northern Alberta (Vermilion Chutes Area)

The investigated area is located in northern Alberta within NTS 1:250 000 scale map sheet 84J. Two relatively small areas of Upper Devonian outcrops are known along the Peace River and Harper Creek (Figure 1). On Peace River, Devonian carbonates are exposed in river's banks and thalweg, between just above Vermilion Rapids and the mouth of Mikkwa Creek, for approximately 10 km. A stretch of approximately 2 km between the rapids and the falls on Peace River is known as Vermilion Chutes. This locale is approximately 75 km downstream along Peace River from Fort Vermilion with the Vermilion Falls at the east end of the chutes, some 7 km upstream from the mouth of Mikkwa River. Along Harper Creek downstream from the mouth of a south tributary called Chamberlain Creek, Devonian carbonates form vertical banks up to 5 m high for at least 3 km.

4.1 Vermilion Chutes on Peace River

A 47 m thick section through the Upper Devonian stratigraphy is discontinuously exposed along 10 km in the banks of Peace River upstream from its confluence with Mikkwa Creek (Norris, 1963). The Devonian / Cretaceous unconformity is known within a few kilometres west of Vermilion Chutes. Beyond the narrow area along the river, the bedrock is covered by Pleistocene and Recent deposits. From outcrop and subsurface data, Norris (1963) defined three stratigraphic units and assigned the two lower ones to the Mikkwa Formation and the upper one to Grosmont Formation. Structural data have been collected from the Mikkwa Formation along an outcrop approximately 700 m long downstream from Vermilion Falls (Figure 16). The lowermost part of the exposed section is approximately 10 m thick and consists of partly dolomitized Stromatopora and Brachiopod-bearing limestone with argillaceous limestone interlayers. The upper approximately 16 m of section which is exposed up to the falls, consists of thick bedded limonite mottled limestone and argillaceous limestone. The falls are formed by this upper mottled unit of the Mikkwa Formation. A wide ledge at the north end of the falls marks the transition to the vuggy reefal dolomite of the Grosmont Formation with abundant hydrocarbon staining. A limited thickness of approximately 1½ m of the lowermost Grosmont Formation is exposed on top of the ledge. For other observations on the Upper Devonian carbonate stratigraphy exposed east of Vermilion Chutes, the reader is directed to Buschkuehle (2003).

Figure 13. Widespread limonitic alteration of Devonian carbonates of northern Alberta. a) Preferential limonitic substitution of borrows within uppermost limestone strata of Mikkwa Formation at Vermilion Chutes (Station RR01-84J-85); b) substitution in limestone strata of the Waterways Formation west of Fort McMurray progresses towards the Devonian/Cretaceous unconformity where mottling grades into complete alteration/recrystallization of limestone to an iron rich fine grained layer (Station RE01-74D-16).

Figure 14. Iron staining in the carbonate wallrock of tensional fractures and joints and along the Devonian (Waterways Formation)/Cretaceous (McMurray Formation) unconformity, north side of the Athabasca River, west of Fort McMurray (Station RE01-74D-19).

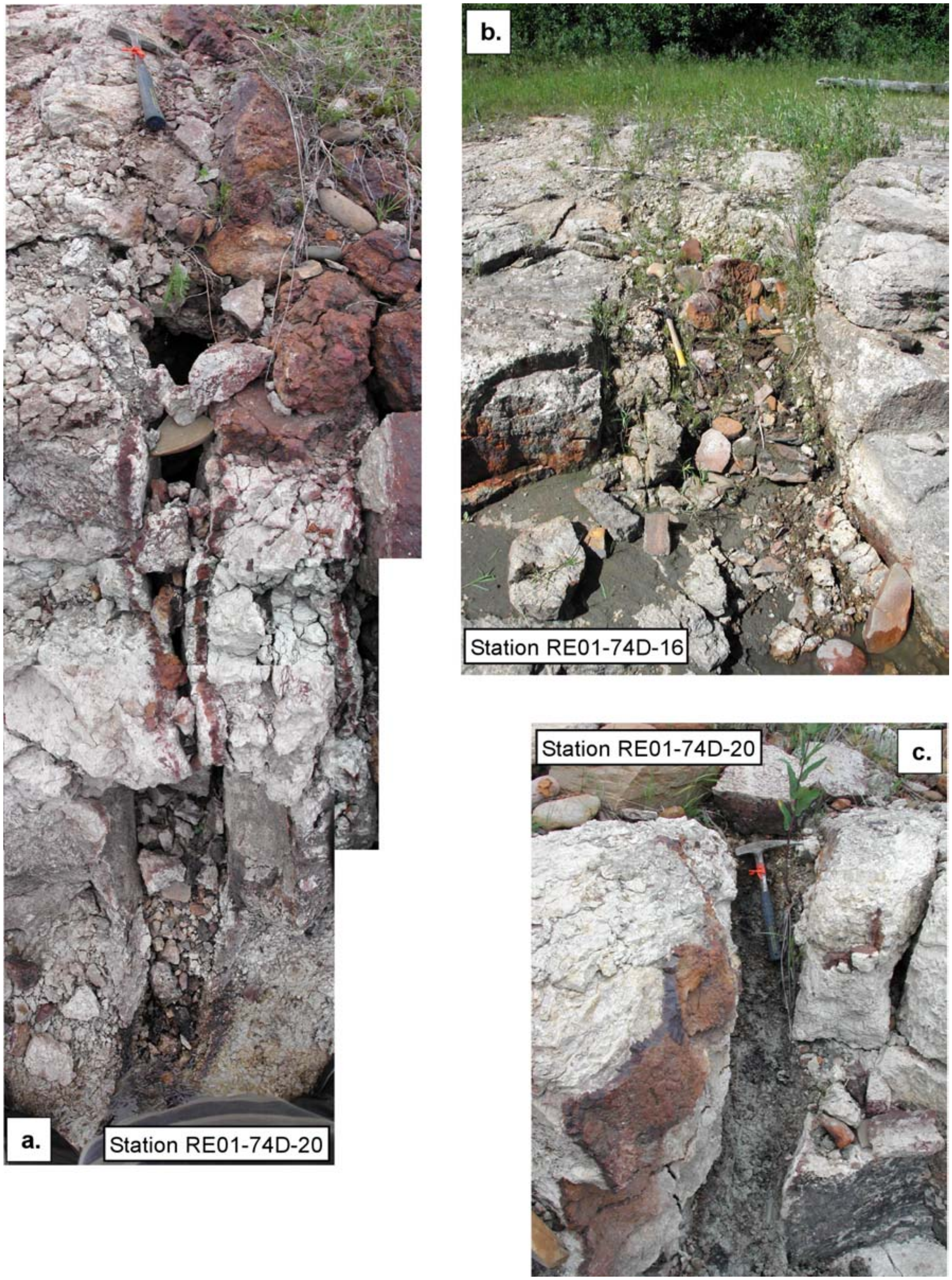

Figure 15. Intense alteration of the Waterways Formation carbonates related to vertical tensional fractures and joints, north side of the Athabasca River, west of Fort McMurray. a) the vertical zone of alteration extends up to 1/2 m in the carbonate wall-rock; b) isolated sulphide nodules in a northerly trending fracture with no visible offset; c) iron and bitumen staining of the wallrock and complete alteration of limestone to an argillaceous material very similar to fault gauge within a tensional fracture.

Figure 16. Carbonate units of the Upper Devonian Mikkwa Formation immediately downstream from Vermilion Chutes, Peace River. a) the outcrop face developed along the dominant set of joints trending southeasterly; b) relationships between bedding and the dominant set of joints (Station RR01-84J-66); c) ledge atop resistant Mikkwa limestone and dolomitic limestone overlain by recessive bitumen-bearing vuggy dolostone of the Grosmont Formation (Station RR01-84J-66); d) orthogonal joint system better expressed in more massive units of the Mikkwa Formation (RR01-84J-64).

4.1.1 Bedding

Bedding planes are subhorizontal with variable local dip within 1° to 5°. A regional northerly to northwesterly strike can be inferred from the trend of the falls. A southwesterly dip of approximately 4° per kilometre was estimated by interpolating data from Vermilion Chutes outcrop and a well at Fort Vermilion (Norris, 1963).

4.1.2 Joints

Two quasi-orthogonal sets of joints similar to those recorded in the Waterways Formation at the Fort McMurray area have been recognized within the carbonate cliffs marking the northern bank of Peace River at, and east of Vermilion Falls (Figure 17). The joint set with azimuths varying between 230° to 250° is definitely predominant, although not always clearly crosscutting other joint sets. It is worth noticing that the local trend of Peace River parallels this joint set, thereby indicating that this dominant joint set may encompass at least the ca. 700 metres width of the Peace River whose local course would then implicitly be structurally controlled. The trend of the dominant joint set recorded by Mikkwa carbonates at Vermilion

Chutes projects into shear zones mapped on the Alberta Shield (e.g., Godfrey, 1980) (see Figure 1 and Figure 18). Surprisingly, tens of square metres of vertical joint surfaces of the dominant joint set contain vague, but consistent brittle linear features that suggest modest sinistral stretching combined with the downdrop of the southern compartment (Figure 19). If normal slip may be the result of local erosion-induced isostatic re-equilibration between the thalweg and river banks, the sinistal stretching is highly intriguing as it lines up with Hudsonian sinistral shear zones in the shield.

4.2 Harper Creek

A 3 to 5 metre thick section of the Mikkwa Formation was examined along a stretch of approximately 100 m on the northern bank of Harper Creek. There, flat laying slightly dolomitic limestone is overprinted by a high-angle minor fault zone trending approximately 100° to 115° (Figure 20). Its orientation and general aspect is similar to the fault zone noticed at Whitemud Falls on Clearwater River. Individual fault planes are locally sealed by coarse secondary calcite, but no significant alteration has been noticed. A few kilometres upstream, at the confluence of Harper Creek with Chamberlain Creek, a penetrative set of joints apparently bisecting the confluence was seen from the helicopter. The locale corresponds to sulphur-rich springs and may deserve further investigation.

4.3 Inferred Structures in Sub-Surface

A Devonian basement fault scarp with approximately the same orientation as the dominant joint set measured in outcrop is suggested by the transition from Devonian basinal shales to platformal dolomite along an east-northeast oriented lineament. The Vermilion Chutes are also located near the axis of the Devonian Hotchkiss Embayment, an inferred zone of subsidence that lines up with the westward projections of shear zones mapped on the Alberta Shield. North of Vermilion Chutes a series of east-north east linear anomalies across southern Caribou Mountains have been recently revealed by directional filtering of aeromagnetic data (Geiger and Cook, 2001), thereby indicating that a local peculiar fabric overprints the generally northerly trending basement grain depicted by aeromagnetic data in northern Alberta (Figure 18). The possibility that Upper Devonian carbonates in this area may be underlain by a linear zone of recurrent strain in the basement is a concept worth pursuing in light of

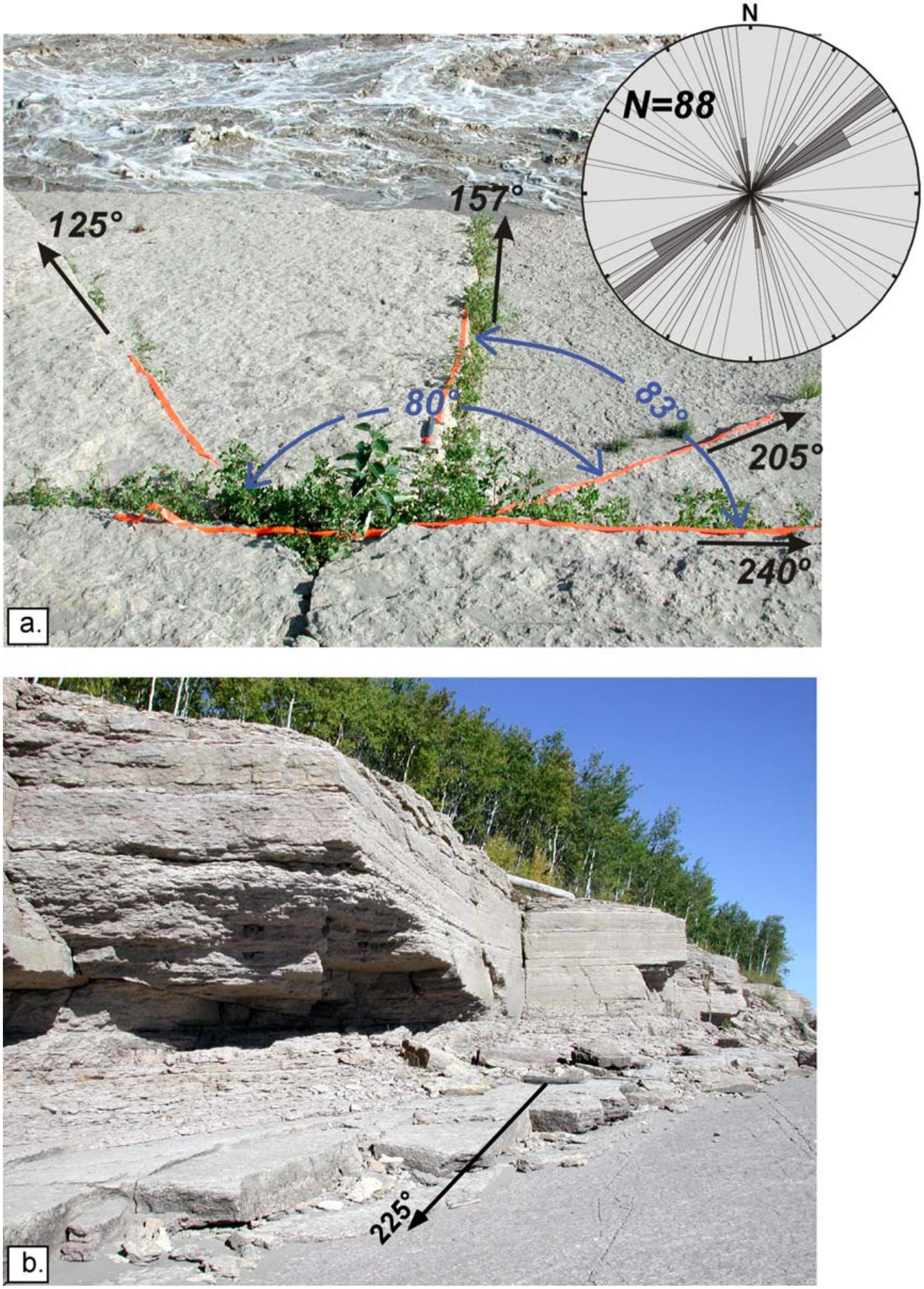

Figure 17. Joint orientation patterns in carbonate strata of the Upper Devonian Mikkwa Formation at Vermilion Chutes, Peace River. a) two systems of 'orthogonal' joint sets: System I, defined by sets parallel and perpendicular to the Cordilleran Orogen, and System II defined by sets trending northerly and easterly (Station RR01-84J-85); attached rose diagram shows the dominance of the northwesterly trending joint set; see text for inferred timing of jointing; b) rectangular blocks in carbonate strata of the Mikkwas Formation defined by bedding joints intersection (Station RR01-84J-66).

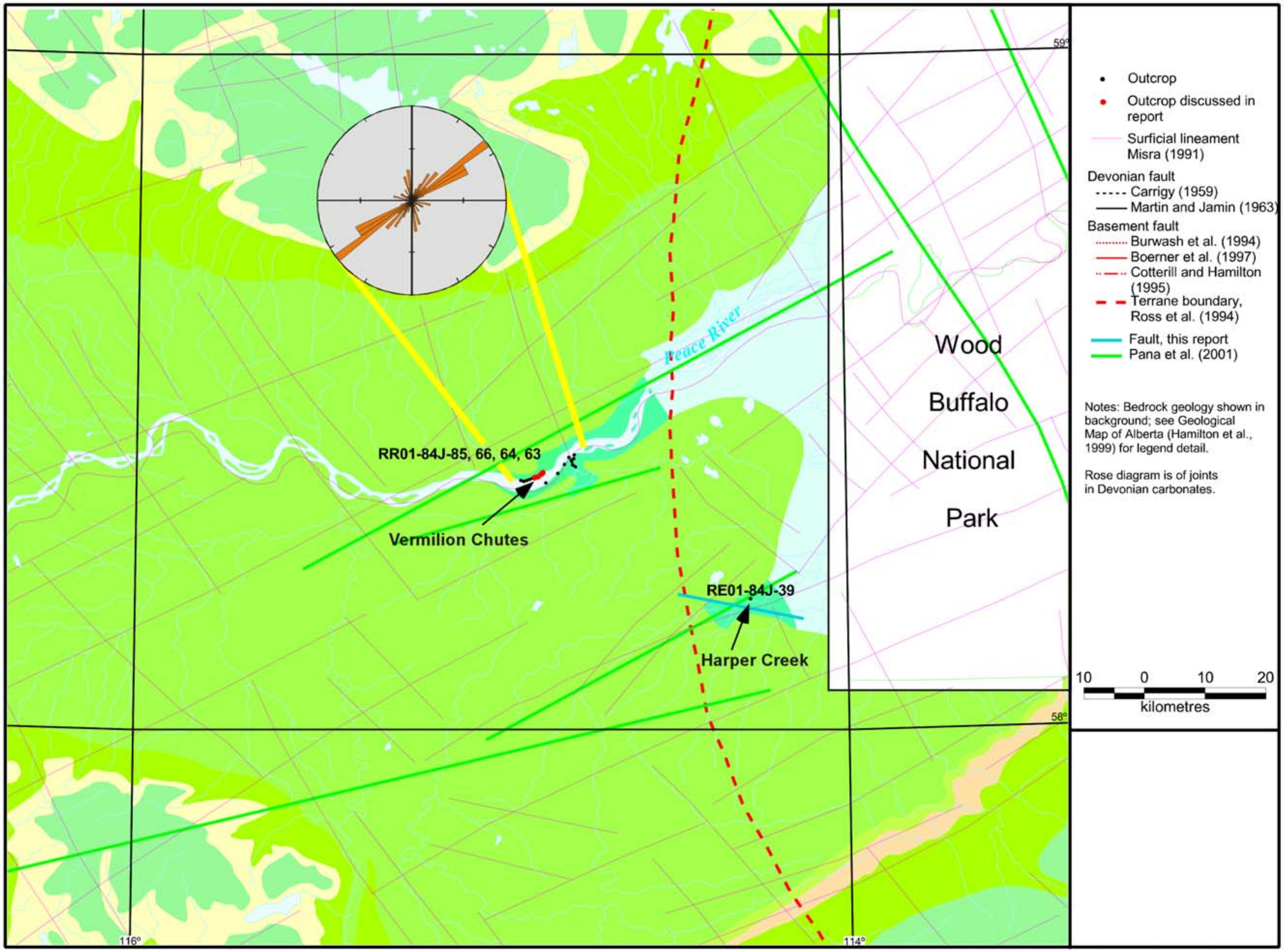

Figure 18. Known and inferred fractures in northeastern Alberta, Vermilion Chutes study area (from Pana et al., 2001).

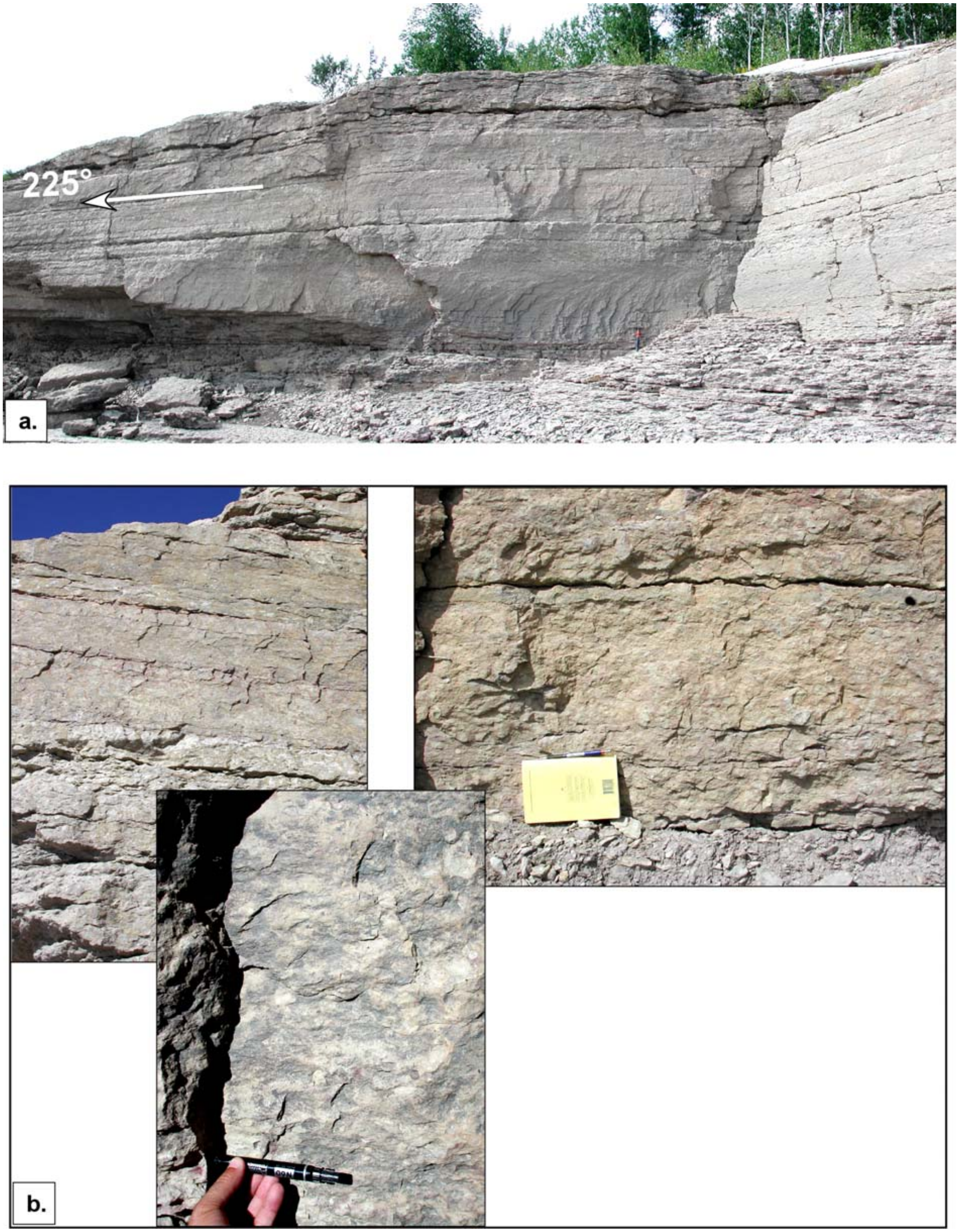

Figure 19. Vague linear structures in the Devonian carbonates of the Mikkwa Formation at Vermilion Chutes. a) plumose structure indicating that the joint opened from northeast to southwest (Station RR01-84J-66); b) vertical shear joints with strikes of N35°E to N75°E contain consistently oriented monor structures similar to the steps of stretching lineation suggesting weak sinistral shear along a subhorizontal axis; from right to left Station RR01-84J-63, -64 and -65.

Figure 20. Minor reverse fault zone (20°/85°) within carbonate strata of the Mikkwa Formation along Harper Creek.

current knowledge on MVT mineralization of Paleozoic carbonates involved in the Cordilleran foreland basin.

5 Joints and Faults as Pathways for Mineralizing Fluids

Field observations in northern Alberta and in particular in the Fort McMurray area provide new evidence that joints/fractures acted as pathways for upwelling mineralizing fluids in the Devonian carbonate succession.

Limonitic mottling is very common in both investigated areas, indicating widespread postdepositional limestone alteration (Figure 18). The dark-brown blotches of Fe-stained limestone generally comprise about 30 to 50 vol. % of the rock. While the mottled limestone can be observed throughout the investigated area, pervasive alteration and replacement of limestone appears more intense in the area west of Fort Mc Murray. Observations at many sections along the Athabasca River west of Fort Mc Murray (e.g., Station RE-19) provide conclusive evidence that the alteration of the Moberley Member of the Waterways Formation is related to fluid movement along vertical joints/fractures (Figure 19). The alteration is seen to line the direct contact of the joint and splay out horizontally at the top of the Devonian carbonates. Near the sub-Cretaceous unconformity, the limestone is totally replaced by a fine-grained to cryptocrystalline rock that does not react with 10% HCl solution. This rock forms a 10 to 15 cm thick limonite-stained layer with finely disseminated to 2-5 mm blebs (up to 10%) of greyish-black sulphide, which probably is pyrite (Figure 14). Rubble within a northerly trending ½ m wide fracture included nodular fragments of massive pyrite and the wall-rock is preferentially coated by a limonitic layer up to 4 cm thick (Figure 15). The ochre to dark brown or black alteration material within and directly adjacent to the joints occasionally contains minor (<5%) pyrite. Whilst most fractures have an Fe-stained 'rind', some other faults show a 'clean rind' with distinctly bleached rock directly adjacent to the fracture (Figure 15a) (Station RE01-74D-019). At the base of station RE01-74D-019, two fractures with greenish-grey fault gouge-like argillaceous material have been noticed (Figure 15c). The azimuth of the near-vertical joint corresponds to the joint set that parallels the deformation front in the Rockies (Station RE-19) or to the northerly trending set. At this locale, the joints in limestone are infiltrated by bitumen from the overlying Mc Murray Formation.

6 Discussion

In the Interior Plains, an ideal exploration target would be the duplication of those geological controls associated with the Pine Point deposits. The discovery of the Pine Point deposits was based on prior knowledge of sphalerite and galena occurrences in the area and an empirical exploration model designed to test the relation between tectonics and mineralization (Campbell, 1967). The outcropping segment of the GSLZ to the northeast is accompanied by a string of sulphide occurrences in the rocks of the Precambrian shield (Campbell, 1967). Faults of this system were thought to have been the conduits for ore-bearing solutions and hence these fluids may have deposited ore bodies when released into overlying sediments. The hypothesis served as a basis for exploration along GSLSZ' strike, which resulted in the initial discovery of entirely concealed and commercially valuable linear array of ore bodies in the Pine Point area.

The principal geological elements in the localization of these deposits hinges on the interplay of: 1) the regionally important fracture in the underlying Precambrian basement, reactivated subsequent to carbonate deposition; and/or 2) a zone of repeated crustal strain that may not be the site of great faults, but rather, belts of pronounced differential movement between a stable highland and an adjacent sedimentary basin or between adjacent areas of positive and negative crustal movement; and finally 3) a lineament of facies change including a porous carbonate host (reefal and/or strained).

1) Geological mapping on the Alberta Shield has shown several regional shear zones in the crystalline basement that trend and extend westerly beneath the Devonian carbonate cover similar to the GSLSZ at Pine Point. The shallow-buried Devonian carbonates that fringe the Precambrian Shield would be the most attractive for exploration because of the projected lower costs of mining. Although much of the prospective outcrop/subcrop carbonate area lies within the Wood Buffalo National Park, other parts are available for surface exploration:

- The southwesterly structural trend of Lake Athabasca (projecting along the northern flank of the Birch Mountains) qualifies as a speculative regional exploration target.

- In the Vermillion Chutes area, gently dipping Upper Devonian carbonates are slightly sheared and placed close to the westward projection of the Warren Shear Zone. Similar to Pine Point, a major Hudsonian shear zone seems to have been followed by post Devonian differential crustal movement.

Both areas in northeastern Alberta are concealed nearly everywhere by surface deposits of glacial drift. The extensive Peace-Athabasca delta deposits obscure the bedrock in this region. Therefore, regional geophysical surveys and limited follow-up by drill hole testing would provide the basis for any lead-zinc exploration program in this region. As well, there is further scope for geochemical exploration in a more focused and detailed way along selected trends rather than the broad reconnaissance reported by Green (1971) over part of this region.

2) Differential movement along the northern and southern flanks of the PRA is believed to have selectively favoured reef growth and subsequent fracturing of the reef and other beds during the Late Devonian-Early Carboniferous arch collapse and development of the Peace River Embayment. The fracturing and possible provision of chemically active thermal waters may have been followed by recrystallization of the reef accompanied by volume changes in the carbonate sediments, by brecciation, collapse structures and possibly deposition of sulphides and other minerals (in short, very similar geological framework as the MVT's in the USA) .

3) At Pine Point, reactivation of the GSLSZ led to the development of radical variations in sedimentary facies. The identification of facies change along lineaments and possible fault scarps within the WCSB, may constitute a first hint to Phanerozoic tectonism. In northern Alberta, Vermilion Chutes are located along a westerly trending lineament of facies change within the Lower Leduc with basinal shales to the north and platformal dolostone to the south (Switzer et al., 1994) (Figure 18). The location of Vermilion Chutes is within a few kilometres from the inferred axis of the Late Devonian Hotchkiss Embayment, a linear zone of enhanced subsidence along the westward projection of the Hudsonian Leland Lakes and Warren shear zones mapped on the Alberta Shield (Godfrey, 1980). Although minor, the Zn anomaly reported by Gulf Minerals Ltd. at Vermillion Chutes warrants further investigation. In central Alberta, the northerly trending Rimbey-Leduc reef chain marks a lineament of drastic facies change with sulphides reported from several wells. This reef lineament is postulated to be controlled by a basement tectonic discontinuity and consequently it is commonly referred to the "Leduc fault chain" although no convincing seismic evidence exists (Haites, 1960, Jones, 1980; Mountjoy, 1980).

7 Conclusions

Alberta encompasses a large part of the WCSB with abundant and widespread Paleozoic carbonate sequences, but there has been very little exploration for or indication of a major lead-zinc deposit within northern Alberta. Models of ore deposits are widely used in mineral exploration as a basis for predicting the exploration potential of areas. Using models with an incomplete descriptive base is a common cause of poor exploration decisions. In view of their limited spatial and temporal distribution, MVT deposits are not simply the products of the normal evolution of sedimentary basins with carbonate platform sequences (Leach et al., 2001). Our field investigations suggest that omission of fractures and tectonism from the MVT empirical model in the WCSB diminishes its predictive power. Several general characteristics of the MVT deposits and occurrences in the carbonates of the WCSB can be extracted by using our field observations in conjunction with existing data on MVT occurrences in the WCSB. Specifically

- Fractures or fault zones are the only conceivable geological/hydrogeological feature that probably would have permitted the ore fluids to be focused into areas (from mine or district scale) where they could mix with other reductive fluids or react with rocks at the site of ore deposition;

- Fluid inclusion temperatures in the ores indicate that hydrothermal ore fluids were hotter than what could reasonably be obtained from burial or advecting basin fluids;

- Tectonically induced, secondary porosity of carbonate rocks appears to be the main trap for ore-bearing fluids. Thus, the occurrence of highly porous reefs in the subsurface of Alberta is a favourable geologic feature for the development of base-metal deposits, but not a critical factor;

- At the relatively low temperatures of MVT ore fluids, only high salinity permits carrying sufficient metal in solution. A source of the dissolved salts is essential for the extraction of metals from crustal sources and to transport the metals to the site of deposition. As well, ore fluids in the foreland are most likely basinal fluids that infiltrated basement fault zones in the basin floor, being directly involved in metal extraction and transport from and through the basement;

- Fluid flow through basement fractures capped by carbonate strata in the Cordilleran foreland may have been driven by a combination of thermal convection and hydraulic pumping.

Therefore, it is suggested herein that the geological environments represented by the carbonate rocks of the Alberta plains are clearly favourable for the development of Mississippi Valley Type lead-zinc deposits.

8 Recommendations

1) Identification of the main MVT pathfinders - basement fractures. The association of lead-zinc occurrences with fractures indicates that fractures, primarily basement fractures, can be used as pathfinders. A regional summary of the tectonics of the WCSB could introduce useful shortcuts in the selection of exploration areas for more detailed study. The digital compilation of known and inferred faults in northern Alberta (Pana et al., 2001) is a starting point. The association of MVT occurrences in the WCSB with fractures, warrants aeromagnetic, seismic and gravity survey data being processed and interpreted. In the Interior Plains much of the Paleozoic carbonate fails to crop out in the potential area of exposure. Thus, regional interpretation of aeromagnetic surveys would serve to provide data on the broad structural framework. The regional interpretive aeromagnetic coverage could be usefully extended

into areas of thin Cretaceous overburden. Following the assumption that MVT deposits are favoured by large-scale faults and reef accumulations, the interpretive aeromagnetic survey approach to defining such features in the Paleozoic carbonates, should be an important step towards the identification of exploration targets.

2) Subsurface data search for base-metal deposits in Alberta. The intensely explored subsurface of the Western Canada Sedimentary Basin, with methodical filing of subsurface data and core under the jurisdiction of the AEUB authority, offers an unparalleled opportunity for a broad-based subsurface data search for base-metal deposits in Alberta. It would seem prudent to harness this mass of data on a selected target area basis and not for the entire Western Canada Sedimentary Basin in Alberta (Godfrey, 1985). An overview of subsurface sulphide occurrences (e.g., Haites, 1960, Turner and MacPhee, 1994) helped identify regions worthy of exploration targeting. A further level of detail and refined evaluation on pilot test areas will be achieved through downhole geophysical logs, lithologs, and core and cuttings samples examination.

9 References

Adams, J., Rostron, B.J. and Mendoza, C.A. (2000): Evidence for two-fluid mixing at Pine Point, NWT; Journal of Geochemical Exploration, v. 69-70, p.103-108.

Anderson, G.M. and Macqueen, R.W. (1988): Ore deposit models – 6. Mississippi Valley-type lead-zinc deposits; *in* Ore Deposits Models, R.G. Roberts and P.A. Sheahan (eds.), Geoscience Canada, Reprint Series 3, p. 79-90.

Bethke, C.M. (1985): A numerical model of compaction-driven groundwater flow and its application to the paleohydrology of intracratonic sedimentary basins; Journal of Geophysical Research, v.90, p. 6817-6828.

Bethke, C.M. and Marshak, S. (1990): Brine migration across North America – the plate tectonics of groundwater; Annual Review of Earth and Planetary Sciences, v. 18, p. 287-315.

Babcock, E. A. (1973): Regional jointing in southern Alberta; Canadian Journal of Earth Sciences, v. 10, no. 12, p. 1769-1781.

Babcock, E. A. (1974): Jointing in central Alberta; Canadian Journal of Earth Sciences, v. 11, no. 8, p. 1181-1186.

Babcock, E. A. (1975): Fracture phenomena in the Waterways and McMurray Formations, Athabasca oil sands region, northeastern Alberta; Bulletin of Canadian Petroleum Geology, v. 23, no. 4, p. 810-826.

Babcock, E. A. and Sheldon, L.G. (1976): Structural significance of lineaments visible on aerial photos of the Athabasca oil sands area near Fort McKay, Alberta; Bulletin of Canadian Petroleum Geology, v. 24, no. 3, p. 457-470.

Buschkuehle, B.E. (2003): Sedimentology and stratigraphy of Middle and Upper Devonian carbonates in northern Alberta: a contribution to the carbonate-hosted Pb-Zn (MVT) Targeted Geoscience Initiative; Alberta Energy and Utilities Board, EUB/AGS, Geo-Note 2002-14, 22 p.

Campbell, N. (1967): Tectonics, reefs and stratiform lead-zinc deposits of the Pine Point area, Canada; Economic Geology, Monograph 3, p. 59-70.

Carrigy, M.A. (1959): Geology of the McMurray Formation, Part III, general geology of the McMurray area; Research Council of Alberta, Geological Division, Memoir 1, 130 p.

Cotterill, D. K. and Hamilton, W. N. (1995): Geology of Devonian limestones in northeast Alberta; Canada-Alberta MDA Project M92-04-14, Alberta Research Council, Alberta Geological Survey, Open File Report 1995-07, 94 p.

Dubord, M. (1987): Carbonate-hosted Pb-Zn potential of northeastern Alberta and the applicability of petroleum data for mineral exploration; Alberta Research Council, Open File Report 1987-07, 41 p.

Eccles, D. R. and Pana D. I. (2003): Metallogenic considerations for Devonian carbonates in the Fort McMurray and Fort Vermilion areas, Alberta: a contribution to the carbonate-hosted Pb-Zn (MVT) Targeted Geoscience Initiative; Alberta Energy and Utilities Board, EUB/AGS, Geo-Note 2002-20, 18 p.

Garven, G., (1985): The role of regional fluid flow in the genesis of the Pine Point deposit, Western Canada Sedimentary Basin; Economic Geology, v. 80, p. 307-324.

Garven, G., Ge, S., Person, S. M. and Svejensky, D.A. (1993): Gensis of stratabound ore deposits in the mid-continent basins of North America, 1. The role of regional groundwater flow; American Journal of Science 293, p. 497-568.

Geiger, H.G. and Cook, A.F. (2001): Analyses of crustal structure from bandpass and directionally filtered potential-field data: an example from western Canada; Canadian Journal of Earth Sciences, v. 38, no. 6, p. 953-961.

Godfrey, J.D. (1973): Stony Islands copper showing, Slave River, Alberta; Alberta Research Council Open File Report 1973-36, 12 p.

Godfrey, J.D. (1985): Lead and zinc – commodity profile; Internal Report to AENR, Alberta Research Council Internal Report, 22 p.

Godfrey, J.D. (1986): Geology of the Precambrian Shield in northeastern Alberta; Alberta Research Council, Map 180.

Green, R. (1971): Geology and mineral resources of northeastern Alberta; unpublished report, Alberta Research Council, 27 p.

Gulf Minerals Ltd. (1975): Vermilion Chutes property, internal report.

Haites, T.B. (1960): Transcurrent faults in Western Canada; Journal of Alberta Society of Petroleum Geologists, v. 8, p. 33-78.

Hamilton, W.N., Langenberg, W.C., Price, M.C. and Chao, D.K. (1999): Geological map of Alberta; Alberta Energy and Utilities Board, EUB/AGS, Map 236, scale 1:1 000 000.

Hoffman, P.F. (1987): United plates of America, the birth of a craton: Early Proterozoic assembly and growth of Laurentia; Annual Review of Earth Planetary Sciences, v.16. p. 543-603.

Holter, M.E. (1977): The Oldman River lead-zinc occurrence, southwestern Alberta; Bulletin of Canadian Petroleum Geology, v. 25, no. 1, p. 92-109.

Hoy, T. (1982): Stratigraphic and structural setting of stratabound lead-zinc deposits in southern B.C.; Canadian Institute of Mining and Metallurgy Bulletin, v.75, no. 840, p. 112-134.

Jones, R.M.P. (1980): Basinal isostatic adjustment faults and their petroleum significance; Bulletin of Canadian Petroleum Geology, v. 28, p. 211–251.

Krebs, W. and MacQueen, R. (1984): Sequence of diagenetic and mineralization events, Pine Point lead-zinc property, Northwest Territories, Canada; Bulletin of Canadian Petroleum Geology, v. 32, no. 4, p. 434-464.

Leach, D.L. and Sangster, D.F. (1993): Mississippi Valley-type lead-zinc deposits; *in* Kirkham, R.V., Sinclair, W.D., Thorpe, R.I., Duke, J.M. (eds.), Mineral Deposit Modeling, Geological Association of Canada, Special Paper 40, p. 289-314.

Leach, D.L., Bradley, D., Lewchuk, M.T., Symons, T.A., Marsily, G. and Brannon, J. (2001): Mississippi Valley-type lead-zinc deposits through geologic time: implications from recent age-dating research; Mineralium Deposita, v. 36, p. 711-740.

Mountjoy, E., (1980): Some questions about the development of upper Devonian carbonate buildups (reefs), Western Canada; Bulletin of Canadian Petroleum Geology, v. 28, no. 3, p. 315-344.

Nelson, W.E. (1970): Report on the Lake Athabasca joint venture, permits 219, 220, 221, 222, 223; Alberta Research Council, Quartz Mineral Assessment Report ZZZ-U-AF-150.

Norris, D.K. (1963): Devonian stratigraphy of Northeastern Alberta and Northwestern Saskatchewan; Geological Survey of Canada, Memoir 313, 168 p.

Ohe, E.L. (1959): Some consideration in determining the origin of ore deposits of the Mississippi Valley type; Economic Geology, v. 54, p. 769-789.

Pana, D., Waters, E.J. and Grobe, M. (2001): GIS compilation of structural features in northern Alberta; Alberta Energy and Utilities Board, Earth Sciences Report 2001-01.

Rice, R.J. (2003): The carbonate-hosted Pb-Zn (MVT) project for northern Alberta-background and year one summary: a contribution to the carbonate-hosted Pb-Zn (MVT) Targeted Geoscience Initiative; Alberta Energy and Utilities Board, EUB/AGS, Geo-Note 2002-19, 13 p.

Sangster, D.F. (1995): Mississippi Valley-type lead-zinc; *in* Geology of Canadian Mineral Deposit Types, (ed.) O.R. Eckstrand, W.D. Sinclair, and R.I. Thorpe; Geological Survey of Canada, Geology of Canada, no. 8, p. 253-261.

Switzer, S.B., Holland, W.G., Christie, D.S., Graf, G.C., Hedinger, A.S., McAuley, R.J., Wierzbicki, R.A. and Packard, J.J. (1994): Devonian Woodbend–Winterburn strata of the Western Canada Sedimentary Basin; *in* Geological Atlas of the Western Canada Sedimentary Basin, G.D. Mossop and I. Shetsen, compilers; Canadian Society of Petroleum Geologists and Alberta Research Council, Special Report 4, p. 165–202.

Turner, A. and McPhee, D. (1994): Analysis of Paleozoic core data for the evaluation of potential Pb-Zn mineralization in northeastern Alberta, Canada-Alberta Partnership on Mineral Development, Project M93-04-032; Alberta Research Council, Alberta Geological Survey, Open File Report 1994-18, 51 p.

Walker, T. (1981): S.M.D.C. Ltd. Wood Buffalo project - final report on exploration activities; Alberta Research Council Quartz Mineral Mineral Assessment Report on permits 6878110001 and 6878110002.

Waters, E.J. and Rice, R.J. (2003): A GIS summary of field data gathered during year one (2001) of the carbonate-hosted Pb-Zn (MVT) project for northern Alberta: a contribution to the carbonate-hosted Pb-Zn (MVT) Targeted Geoscience Initiative; Alberta Energy and Utilities Board, EUB/AGS, Geo-Note 2002-22, CD.

Wheeler, J.O., Hoffman, P.F., Card, K.D., Davidson, A., Sanford, B.V., Okulitch, A.V. and Roest, W.R. (1996): Geological map of Canada/Carte géologique du Canada, "A" Series Map 1860 A, 1:5 000 000; Geological Survey of Canada.