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Preliminary Geologic Interpretation of SAR Data, Yellowknife–Hearne Lake Area, N.W.T.

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ABSTRACT. Airborne, narrow swath, C-band synthetic aperture radar (SAR) imagery, obtained from the Yellowknife-Hearne Lake area, essentially reflects the geomorphology or landforms of the region. These in turn can be readily related to specific lithologies, rock masses, structure and cultural features. Terrain analysis using textural and tonal (brightness) characteristics of the radar images along with drainage and lakeshore characteristics permitted definition of several lithologic classes: Granite terrain type-1, generally the brightest (lightest) area, has a "coarse" mottled signature, reflecting the hummocky surface characteristic of granites in this area. Metasedimentary terrain is typified by an intermediate tone, a thinly laminated texture reflecting bedding and angular shorelines of some lakes. Metavolcanic terrain is subordinate in area and lacks well-defined textural or tonal characteristics. It is most easily recognized as parallel ridges with little or no curvature. The city of Yellowknife is readily identifiable by its bright signature and rectangular pattern or texture.

Lineaments, recognized by the alignment of rivers and shorelines, are greatly enhanced by bright radar reflections from northerly facing cliffs and radar shadow (zero signal return) of southerly facing cliffs. Several major structural lineaments in the area, known from aeromagnetic and geological maps (diabase dykes, faulted contacts, etc.) are readily apparent in the SAR imagery, as are numerous extensions and subsidiary lineaments. Circumstantial evidence suggests that post-Precambrian and neotectonic activity may be related to lineaments.

Key words: synthetic aperture radar (SAR), Yellowknife–Hearne Lake area, terrain analysis, lineaments, neotectonics

RÉSUMÉ. L'imagerie aéroportée, figurant un étroit ruban, obtenue avec le radar à antenne synthétique (RAAS) dans la bande C, dans la zone Yellowknife-lac Hearne, reflète essentiellement la géomorphologie ou les configurations du terrain de la région. Ces dernières à leur tour peuvent être facilement reliées à des lithologies, masses rocheuses, structures et attributs culturels particuliers. Des analyses de terrain à l'aide des caractéristiques de la texture et de la tonalité (brillance) des images radar, couplées au drainage et aux caractéristiques côtières ont permis de définir plusieurs classes lithologiques: le terrain granitique de type 1, correspondant généralement à la zone la plus brillante (la moins foncée), a une signature « rugueuse », chinée, qui reflète le bossellement de la surface particulier aux granites de la région; le terrain métasédimentaire est caractérisé par une tonalité intermédiaire, une texture feuilletée mince reflétant une stratification, ainsi qu'un contour angulaire pour certains lacs; le terrain métavolcanique occupe une superficie plus petite et possède des caractéristiques bien définies quant à la texture ou la tonalité. On le reconnaît facilement à ses crêtes parallèles qui ont peu sinon pas du tout de courbure. On distingue très aisément la ville de Yellowknife grâce à sa signature lumineuse et à son plan ou à sa texture rectangulaire.

Les linéaments, reconnaissables à l'alignement des rivières et des côtes, sont bien mis en relief grâce à la brillance des réflexions radar provenant des falaises orientées vers le nord, et à l'ombre radar (écho nul) provenant des falaises orientées vers le sud. Plusieurs des grands linéaments structuraux de la région, connus d'après des cartes aéromagnétiques et géologiques (filons de dolérite, contacts faillés etc.), sont très visibles sur les images RAAS, de même que de nombreuses extensions et linéaments subsidiaires. D'autres preuves secondaires laissent à penser qu'une activité post-précambrienne et néotectonique pourrait être reliée aux linéaments.

Mots clés: radar à antenne synthétique (RAAS), zone Yellowknife-lac Hearne, analyse de terrain, linéaments, néotectonique

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INTRODUCTION

"Radar" is the acronym for radio detection and ranging. It operates in the radio and microwave bands of the electromagnetic spectrum ranging from a metre to a few millimetres in wavelength and is an active system in so much as it provides its own illumination. The principles of radar geology are described in several textbooks on remote sensing (e.g., Drury, 1987; Sabins, 1987; Trevett, 1986). The main factors are: 1) the incidence angle between the radar beam and the ground, which is related to the slope of the ground in the direction of the beam; 2) the surface roughness, which is a function of the radar wavelength — the rougher the surface, the more the beam energy is scattered and reflected back to the antenna; 3) the complex dielectric constant — soil moisture will increase the dielectric constant and the brightness or reflectivity of the surface; and 4) the look direction — structures perpendicular to the look direction (parallel the flight direction) are enhanced.

In geologic interpretation, it is worthwhile to keep in mind the analogy that the radar imagery approximates a shaded relief map and the landforms shown should be interpreted using principles of geomorphology. It expresses bedrock structure, bedrock lithologies, surficial deposits, vegetation, hydrology and in some cases snow or ice. The ability to interpret bedrock geology or surficial geology will depend on the relative significance of all these factors and vary from area to area.

The Yellowknife–Hearne Lake area of the Northwest Territories was selected for preliminary study because it is a relatively typical area of the northern Canadian Shield, with well-known geology and mineral resources and excellent accessibility and logistical support. Other geological studies of synthetic aperture radar (SAR) imagery have been done for areas of the southern Precambrian Shield in Ontario by Mussakowski *et al.* (1989) (Michipicoten - Wawa area) and Slaney and Misra (1988) (Sudbury area). Fabbri *et al.* (1989) reported on the Bathurst Inlet area along the arctic coast at the northern margin of the Canadian Shield. However, this area contains a large proportion of cover of unmetamorphosed Proterozoic strata, as well as a large area of tidal coastline, and is generally less representative of the shield.

The radar imagery for the Yellowknife–Hearne Lake area was acquired by the Canada Centre for Remote Sensing's (CCRS) C/X-SAR system as one of several projects of the Radar Data Development Program (RDDP) organized by the

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Radarsat Project Office. Figure 1 shows the geometry and parameters used in this project. The CCRS C/X-SAR system is carried in a long-range Convair 580 aircraft. The Canadian-designed and -built system is described by Livingstone *et al.* (1987). The Radarsat project, Canada's major space effort, is directed at the design, launching and operation of its first remote sensing satellite with a state-of-the-art C-band SAR system as the principal sensor. Scheduled for launching in the next few years, Radarsat and its SAR are expected to produce significant contributions to Canadian research and development, renewable and non-renewable resource sectors, arctic shipping, sovereignty and economy through the sale of technology and imagery.

GEOLOGY OF THE YELLOWKNIFE–HEARNE LAKE AREA

The Yellowknife–Hearne Lake area covers the central and southern parts of the Yellowknife supracrustal basin (Fig. 2). The area is generally flat and typical of the Canadian Shield. However, in detail the country is rugged, with rock hills and ridges rising abruptly from lake or muskeg to heights of more than 65 m (Henderson, 1941).

The bedrock geology was compiled by Henderson (1985) at 1:250 000 scale, while the Blatchford Lake Complex was mapped by Davidson (1981) and the Cameron River volcanic belt by Lambert (1988) at 1:50 000 scale. Regionally, the geology is relatively simple and typical of the Archean granite-greenstone terrane, albeit sediment dominated (Fig. 2). The main feature is the Yellowknife supracrustal basin, a large area of folded metasediments with extensive metavolcanic rocks near its margins. These rocks, collectively known as the Yellowknife Supergroup, are intruded by various granitic rocks. Pre-Yellowknife Supergroup or basement gneisses and granites are present as the Sleepy Dragon Complex in the northeastern part of the study area. The Proterozoic Blatchford Lake Complex and various diabase dyke sets and other rock types account for less than 5% of the area (Henderson, 1985).

Baragar and McGlynn (1976) proposed a model for the development of Archean greenstone belts, that envisioned a thin (15-20 km thick), continuous sialic crust upon which a volcanic pile accumulates. The pile induces a downwarp in the crust and induces melting at its base. This in turn feeds plutons that rise through the crust and eventually the volcanic pile. The well-documented Yellowknife volcanic belt, which forms the western margin of the Yellowknife supracrustal basin, has also been used by Henderson (1981) to develop a genetic or evolutionary model for Archean supracrustal basins and volcanic belts in the Slave Structural Province. This model involves extensive block faulting, with mafic volcanism developing locally along basin bounding faults, but not in the main part of the basin. The basins were floored not by oceanic crust but by large down-dropped blocks of granitic basement. The basins were filled mainly with turbidites from surrounding uplifts and lesser amounts of volcanic debris from felsic volcanic centres. Helmstaedt and Padgham (1986) questioned the assumption of crustal thickness required by this ensialic model and noted the absence of modern examples with thick sequences of submarine volcanic rocks. They proposed a proto-oceanic basin similar to the Red Sea or a back arc basin. Later, Helmstaedt *et al.* (1986) described mafic multiple dykes at the base of the volcanic sequence that are similar to atypical ophiolites of modern ocean basins and evidence for Archean sea floor spreading. Fyson and Helmstaedt (1988) have recently proposed a plate tectonic model for the Yellowknife supracrustal basins of the Slave Province. The mafic volcanics are viewed as megaxenolithic remnants of ocean crust on the periphery of granitoid plutons (Fig. 3). Kusky (1989) proposed a compressional island-arc accretionary-prism model for the formation of the Slave Province.

In the Yellowknife supracrustal basin, parallelism of major folds and refolds (Fig. 2) as well as cleavages of different generations "suggest intermittent control of movements by a fixed template of underlying fractures" (Fyson and Helmstaedt, 1988:307). Numerous granitic plutons in the basin have obliterated most of the earlier structures in their vicinity (Drury, 1977; Fyson, 1982, 1984a,b).

The area has important mineral resources and potential. Gold has been mined from giant shear zones in mafic volcanics at Yellowknife for more than 50 years. Both the NERCO-Con and Giant mines are significant Canadian producers of gold. Numerous gold-bearing quartz veins are known in the metaturbidites of the Yellowknife Supergroup (Padgham, 1986; Stokes *et al.*, 1989). One of the most productive of these, the currently operating Ptarmigan mine, has seen sporadic production since the early 1940s. The Camlaren mine at Gordon Lake and the Thompson-Lundmark mine at Thompson Lake are other important past producers.

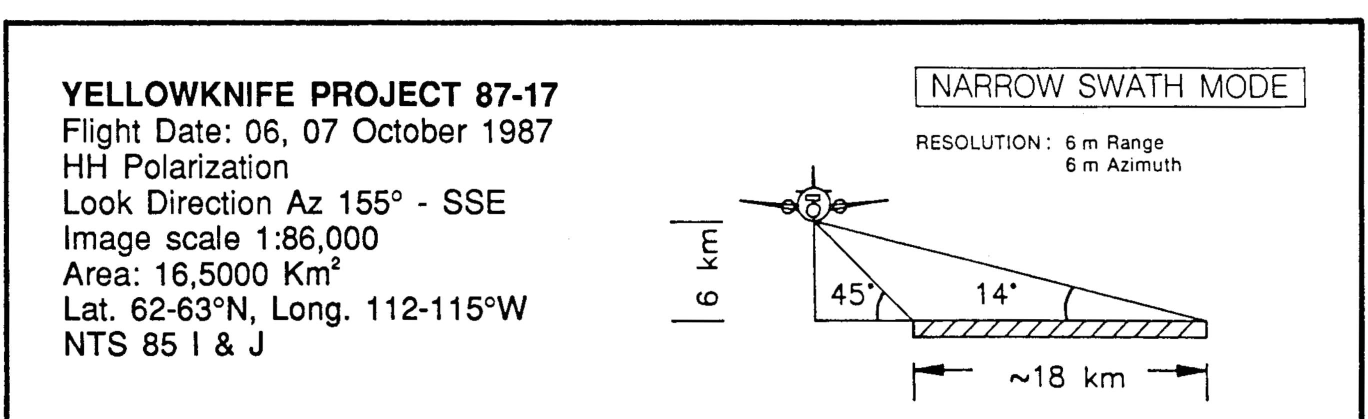

FIG. 1. Operating geometry of CCRS C-band radar in narrow swath mode.

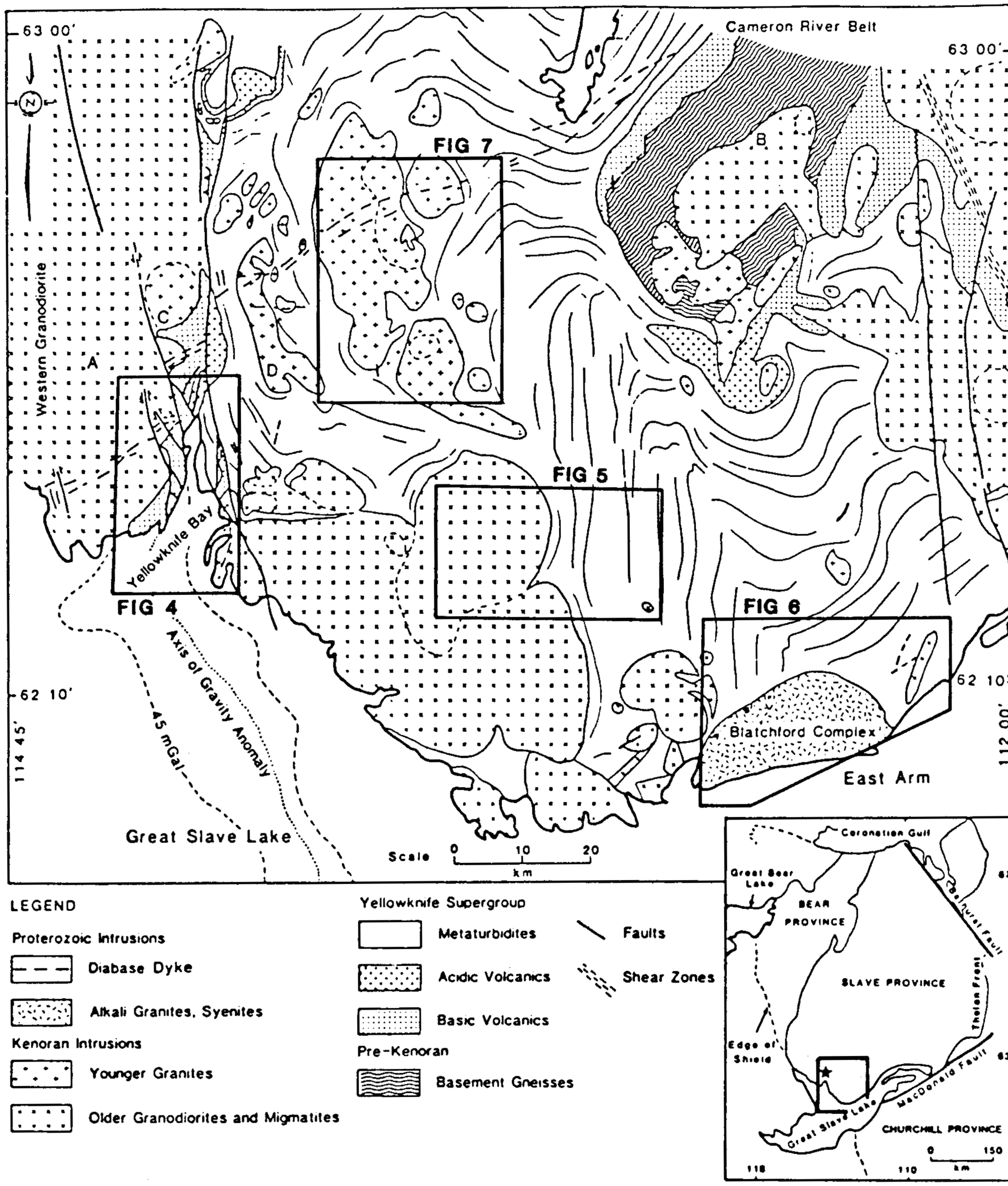

FIG. 2. Generalized geological map of the Yellowknife supracrustal basin showing the location of Yellowknife greenstone belt at Yellowknife Bay (see star on inset map) (from Helmstaedt and Padgham, 1986). Fold trends in metasediments (after Fyson, 1984a).

Considerable lithium resources are present in the pegmatites of the area. Lithium is considered vital to the development of battery technology and thermo-nuclear fusion power (Lasmanis, 1978). In addition, potentially economic beryllium, niobium, tantalum, yttrium, zirconium and rare earth elements are present in pegmatites and the central core of the Blatchford Lake Complex (Trueman *et al.*, 1988).

YELLOWKNIFE–HEARNE LAKE SAR IMAGERY

Our analysis of the Yellowknife–Hearne Lake SAR imagery follows the procedure outlined by Sabins (1987:215), namely, outlining shorelines and drainage, definition and outlining of terrain categories, mapping geologic structures and lineaments and evaluation by comparison with existing maps. Our interpretation combines the use of tone, texture, pattern, shape, context and scale of photo-geological interpretation with radar attributes (Table 1) and our knowledge of the area.

The area is generally flat, like much of the Canadian Shield; therefore problems encountered with radar imagery in more rugged environments, such as foreshortening, overlap and distortions, are insignificant. On the other hand, relief is sufficient to enhance fault- or fracture-related valleys and outline bedding and layering in many outcrop areas. Figures 4-7 illustrate selected areas of the radar imagery.

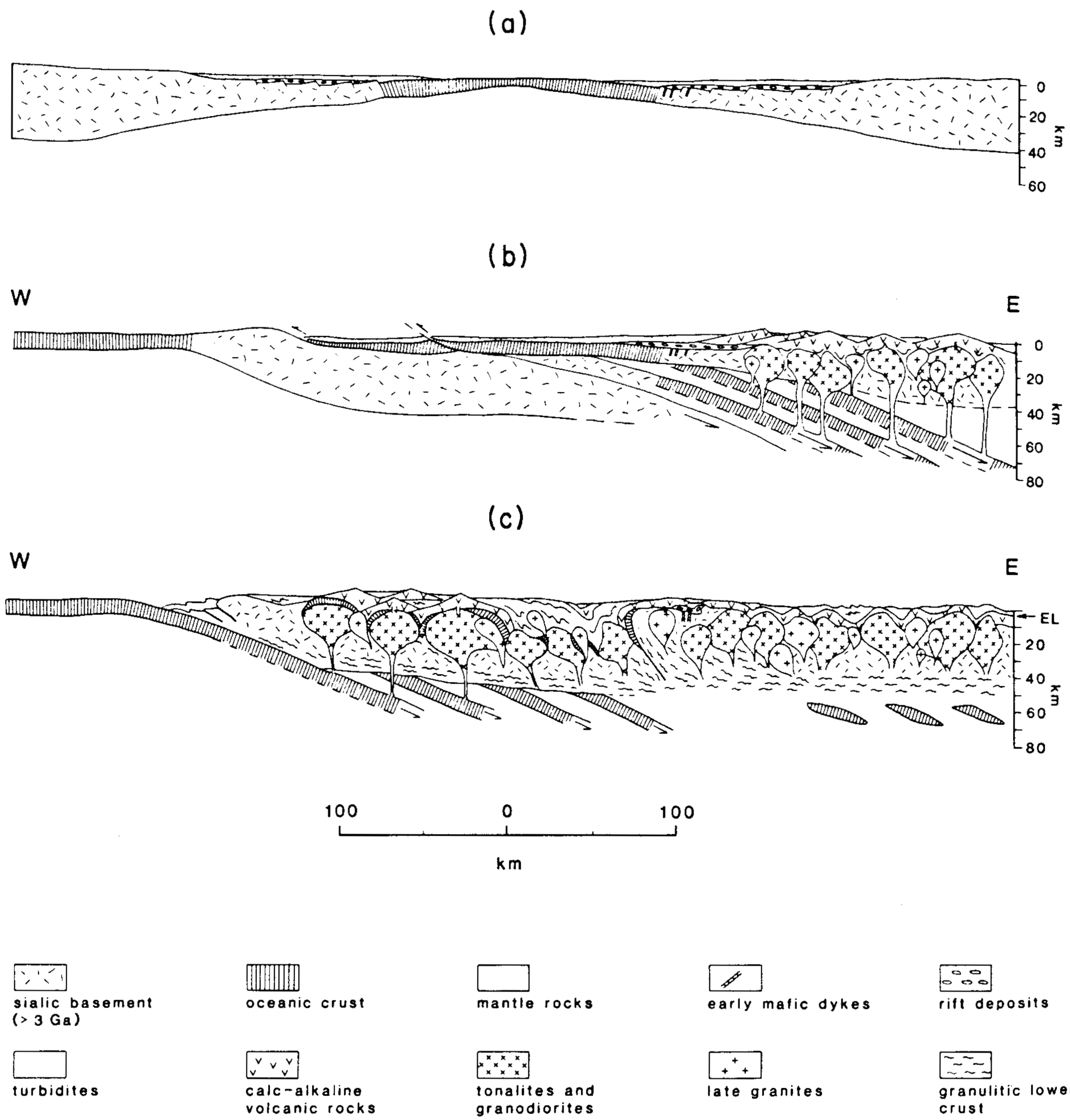

FIG. 3. Plate tectonic model for the evolution of the Slave Province (from Fyson and Helmstaedt, 1988). a) Rifting of pre-3 Ga sialic basement to produce oceanic crust preserved in Yellowknife type greenstone belts. b) Closure of basin, obduction of oceanic crust in western Slave Province; subduction and calc-alkaline magmatism in eastern Slave Province. c) Tectonic underplating by shallow subduction of western Slave Province and westward migration of calc-alkaline magmatism. Deformation and metamorphism of obducted greenstones and formation of shear zones in granulitic lower crust. The present erosion level (EL) must be viewed being approximately only, as uplift was not uniform throughout the Slave Province.

TABLE 1. Typical features and signatures on Yellowknife–Hearne Lake C-SAR imagery (modified from Sabins, 1987:181, Table 6.1)

Image signature	Image tone	Terrain feature	Cause of signature
Highlights	Bright	Steep slopes and scarps facing toward antenna (faults or fractures)	Much energy is reflected back to antenna
Shadows	Very dark	Steep slopes and scarps facing away from antenna	No energy reaches terrain; hence there is no return to antenna
Diffuse surface - rough	Bright - intermediate	Ridges of outcrop with sparse or no vegetation (commonly granite)	Considerable energy reflected back to antenna
Diffuse surface	Intermediate	Low outcrop, rock with considerable vegetation	Vegetation (mainly trees) scatters energy in many directions, including back to antenna
Diffuse surface - smooth	Dark - intermediate	Flat muskeg and swamp vegetation consists of grass, moss, lichen and sedges	Some energy is reflected, most is scattered, some may penetrate surface
Corner reflectors	Very bright	City of Yellowknife, Yellowknife River bridge, houseboats	Intersecting planar surfaces strongly reflect energy back toward antenna
Specular surfaces	Very dark	Calm water, roads, airport runways	Smooth horizontal surfaces totally reflect energy away from antenna (angle of reflectance is opposite to angle of incidence)

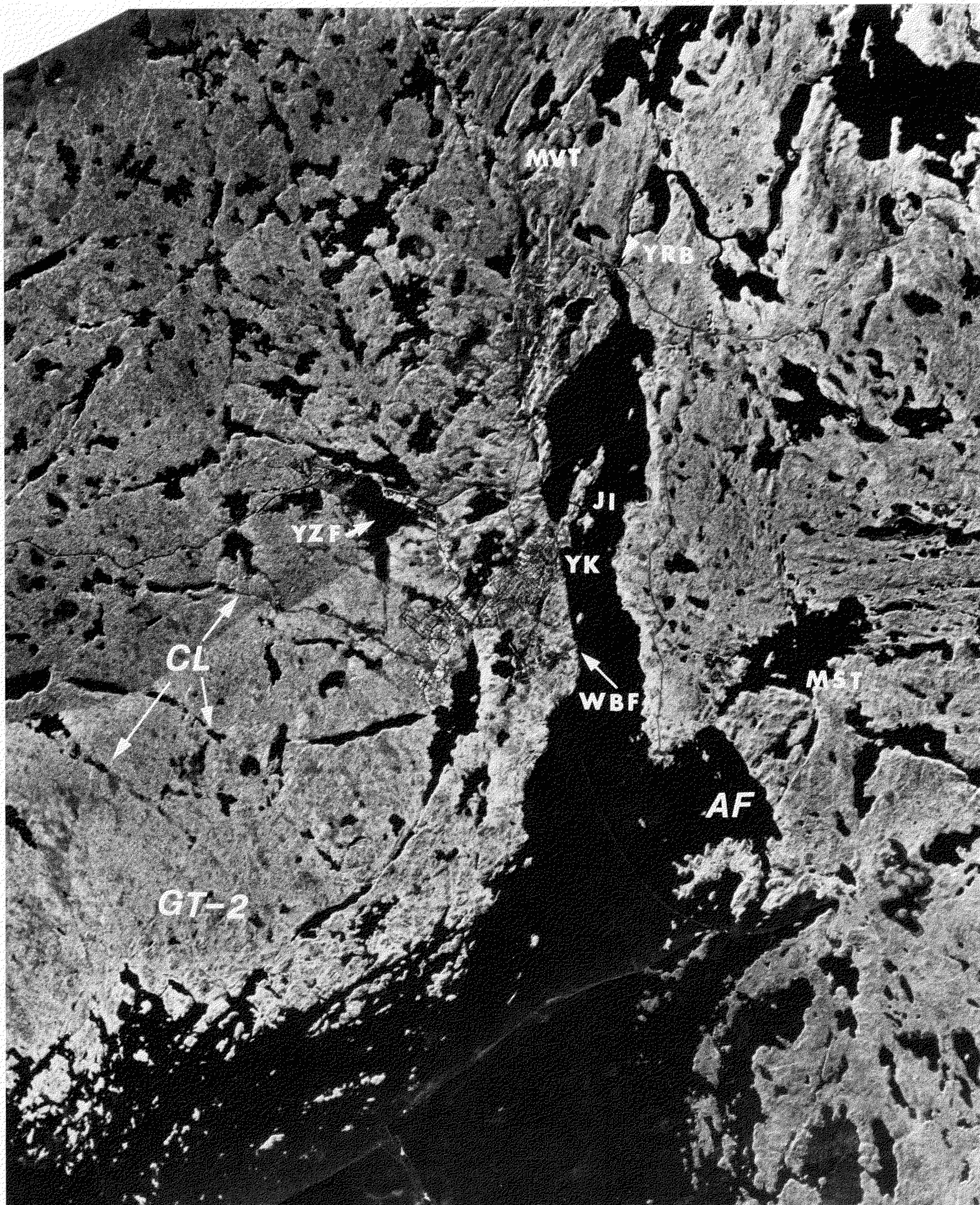

FIG. 4. Synthetic aperture radar (SAR) image of Yellowknife Bay area: *AF* - Akaicho fault, *WBF* - West Bay fault, *MST* - metasedimentary terrain, *MVT* - metavolcanic terrain, *GT-2* - granite terrain type-2, *YK* - city of Yellowknife, *YRB* - Yellowknife River bridge, *JI* - Jolliffe Island, *YZF* - Yellowknife airport, *CL* - curvilinear lineaments.

Terrain Analysis

Several terrain types, in large part related to underlying bedrock geology, are fairly obvious. However, various complexities produce ambiguities in many parts of the area.

Granite terrain-1 (Figs. 5-7) is one of the most distinctive. It typically has an intermediate to bright (light) tone and "coarse" mottled texture that reflects the hummocky surface, characteristic of many granites in the area. Typically this terrain contains many small lakes and lacks obvious internal structure (Defeat Lake, Wedge Lake) or has concentric (Hidden Lake) or more rarely radial structures (Harding Lake). Southwest trends in a small pluton south of Donore Lake may be related to glaciation.

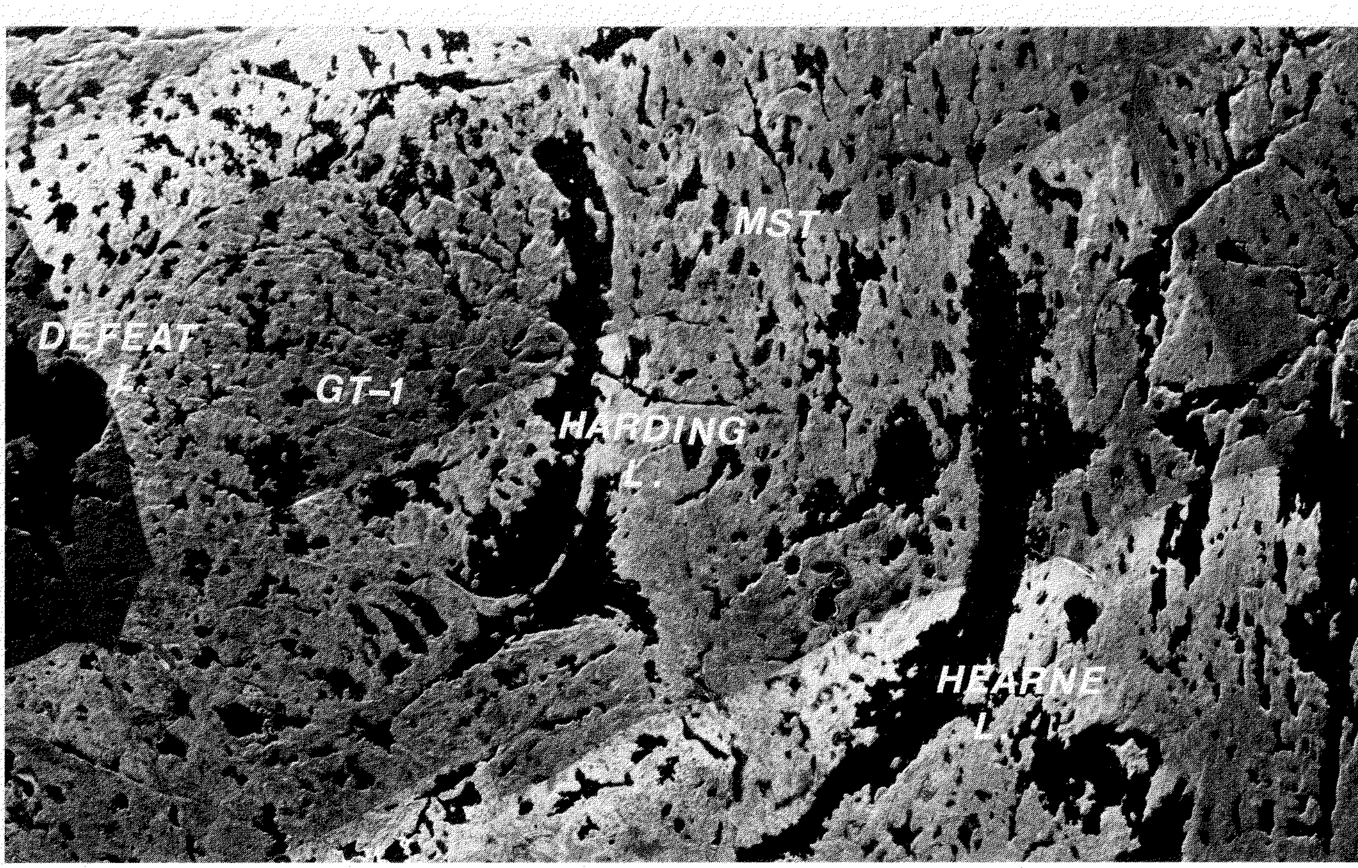

FIG. 5. SAR image of Defeat Lake–Harding Lake–Hearne Lake area: *GT-1* - granite terrain type 1, *MST* - metasedimentary terrain. Note radial pattern of lakes in circular granite bodies southwest of Harding Lake.

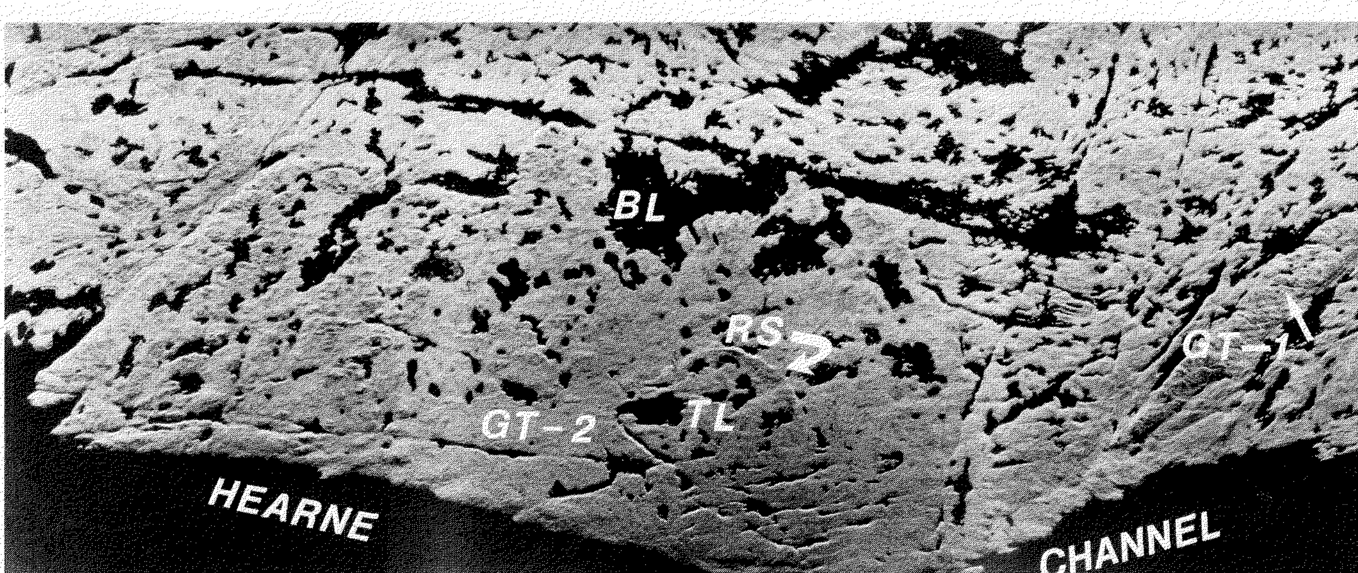

FIG. 6. SAR image of Blatchford Lake area: *BL* - Blatchford Lake, *TL* - Thor Lake, *RS* - rim syenite, *GT 1* - granite terrain-type 1, *GT-2* - granite terrain-type 2.

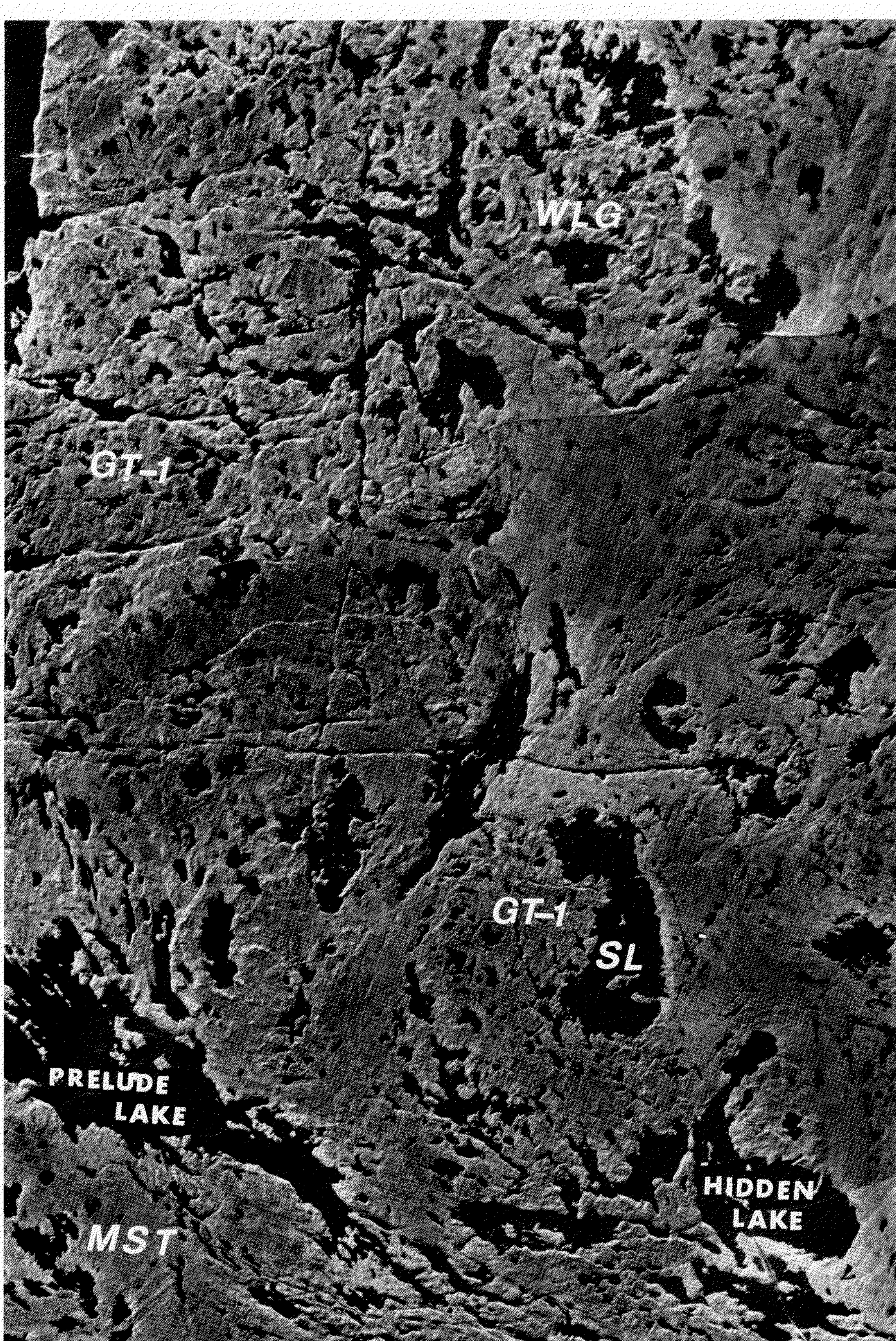

FIG. 7. SAR image of Prelude Lake–Hidden Lake area: *GT-1* - granite terrain-type 1, *MST* - metasedimentary terrain, *SL* - Sparrow Lake, *WGL* - Wedge Lake granite. Note circular structure in Hidden Lake granite and refolded metasediments south of Prelude Lake.

Granite terrain-2 (Figs. 4,6) has a uniform grey tone, typical of fairly low, flat topography. A large portion of this terrain is covered by muskeg or swamp vegetation types. The Western Plutonic Complex (west of Yellowknife Bay) and the Grace Lake Granite and Thor Lake Syenite units of the Blatchford Lake Intrusive Complex are two of the best examples. Gravity modelling of the Blatchford Lake Intrusive Complex (Birkett *et al.*, 1989) suggests it is a saucer-shaped tabular body. The SAR imagery displays northeast-trending block faults, southerly downstepped, in the southeast part of the complex (Figs. 6,8C).

Metasedimentary terrain (Figs. 4-7) also has an intermediate tone and includes a large proportion of the study area. However, this terrain typically has a fine laminated texture that reflects bedding and large folds. Lakes, islands and drainage help outline the bedding in this terrain, as shoreline segments are mainly parallel or normal to bedding (Harding Lake, Hearne Lake and Watta Lake area). Tight isoclinal fold patterns are obvious and common in much of this terrain. They should not be confused with isoclinal folding of thicker layered units in the Sleepy Dragon Complex, which can be seen on the imagery and has been mapped by Henderson (1985).

Metavolcanic terrain (Fig. 4) is subordinate in area and does not have as well-defined textural or tonal characteristics. It is best developed as a series of large parallel ridges north of Yellowknife (the northern Yellowknife volcanic belt) and to a lesser extent in the Beaulieu River–Cameron River volcanic belts. These ridges may be caused by more resistant felsic volcanic units or possible gabbroic sills.

Quaternary terrain: The Yellowknife–Hearne Lake area does not have thick or extensive surficial deposits. Henderson (1985) mapped parts of an esker-delta complex northeast of Hearne Lake, which correspond to a very small area of very fine dark and bright spots on the SAR imagery. This area corresponds to a sandy upland with sparse vegetation, probably due to dry, well-drained soil conditions.

Undifferentiated terrain includes areas where characteristics are not developed or recognizable at the scale and resolution of the imagery.

Urban or cultural area, like the city of Yellowknife (Fig. 4), is readily identified by its bright tonal signature and rectangular pattern or texture. The Yellowknife River bridge and houseboats moored on the west side of Jolliffe Island act as corner reflectors, with very bright images. Runways at the Yellowknife airport and any unpotholed roads in the area are very dark (black) and appear underwater to an air photo interpreter. Their smooth surface, less than 10 cm relief, acts as a specular reflector — that is, all the energy is reflected away from the radar antenna. Adjacent to paved runways, the flat sand plain is almost as dark as the runways themselves. In this area, trees have been removed and the remaining vegetation consists of fireweed and grasses.

Water: All standing bodies of water, including Great Slave Lake, are specular reflectors. With the exception of the cultural features just mentioned and a few narrow lines representing radar shadows of south- to east-facing cliffs, all the black areas represent open water. Water accounts for a considerable proportion of the area and its outline and distribution are clearly and accurately shown on the imagery.

Structural Analysis

The structural geology of the Yellowknife–Hearne Lake area is extremely complex. This is evident in the SAR imagery, but its comprehensive analysis is far beyond the scope of this paper and the SAR imagery. Nevertheless, a great deal of structural information is evident and we will briefly attempt to outline what can be seen and its possible significance.

Folding: Large isoclinal folds are evident in the basement Sleepy Dragon metamorphic complex, southwest of Sleepy Dragon Lake (Basement Complex of Fig. 2). Henderson (1985:91) suggested that most of this folding may have taken place before deposition of the Yellowknife Supergroup.

Metaturbidites of the Archean Burwash Formation, which fills most of the Yellowknife supracrustal basin, are complexly folded on regional through microscopic scales. A two-dimensional picture of the larger folds is evident on the SAR imagery as fine rows distinguishable by subtle tonal changes and is readily obvious from lakes and shorelines. Early rifting and block faulting, gravitational sliding from uplifted areas and especially diapiric rise of granite and granodioritic intrusions have each contributed to this folding. A late regional compression may have modified some of these folds. The reader is referred to papers by Drury (1977), Fyson (1982, 1984a,b) and Stokes *et al.* (1989) for more detailed discussion.

Granitic diapirs: Henderson (1985) has mapped two main groups of granitic plutons in the Yellowknife supracrustal basin: the Defeat Plutonic suite (included in the older granodiorites of Fig. 2 and found mainly in the south-central and western areas) and the Prosperous Plutonic Suite (the younger granites of Fig. 2, found mainly in the north-central area). These granites are diapirs, dome-like structures produced by low-density material (hot granite) rising through a high-density cover (basalt and turbidite). Some develop synclines around their rim as compensation for the rise of granite. Diapirism appears to be an essential factor in the tectonic and metamorphic history of the Canadian Shield and cannot occur without appreciable folding of the supracrustal cover rocks, as is the case in the Yellowknife area.

These plutons are readily apparent on SAR imagery but not distinguishable as to plutonic suite. Most are circular in shape and range from 20 to less than 1 km diameter. Many appear to be structureless, but a few show concentric structure (Hidden Lake with ridges [Fig. 7], Watta Lake with lakes and valleys), radiating features (Harding Lake [Fig. 5]), multiple intrusion (Harding Lake) and marginal ridge and adjacent moat and rim syncline development (Wedge Lake [Fig. 7]).

Lineaments are linear topographic or tonal features on the terrain and on images, maps and photographs. Numerous lineaments have been recognized in the Yellowknife–Hearne Lake area on topographic maps, magnetic maps, air photographs and satellite imagery (Landsat multispectral and Seasat SAR images). However, the airborne C-band SAR imagery used in this study and Seasat imagery inherently enhances lineaments, particulary those trending in a northeasterly direction perpendicular to the look direction of the radar system. In this case, bright tones correspond to west- to north-facing valley walls, which are good radar reflectors, in sharp contrast to black radar shadows of south- or east-facing valley walls (Figs. 4,6,7). This effect in turn makes a linear chain of small lakes, separated by depressions with north- and/or south-facing walls or cliffs, appear all the more striking or obvious.

Most of the major lineaments in the area are large, nearly straight faults of various ages, but mainly within the Proterozoic. These faults can be traced for up to 100 km in length, show up to 4.9 km of horizontal displacement and mainly trend north-northwesterly (Henderson, 1985:100-103). Other prominent lineaments represent large fractures or joints related to diabase dyke swarms. Lineaments and their interpretation are discussed further in the next section.

TECTONICS

Archean Tectonics — Pre- to Post-Turbidite

Probably the oldest structural lineaments in the area are the northerly trending margins of the Yellowknife supracrustal basin that may reflect early rifting of crust (Fig. 2). Most of the faulting related to volcanism and turbidite deposition appears to be local and folded or otherwise obscured by ductile deformation related to diapirism and metamorphism.

Proterozoic Tectonics

Proterozoic dykes, faults and fractures of several ages are present in the study area. Both north-northwest and east-northeast are preferred directions. The radar imagery clearly shows faults mapped by Henderson (1985: Map 1601A, Fig. 76), as well as several documented extensions and parallel structures. The famous West Bay and Akaitcho faults (Jolliffe, 1942, 1946) that mimic the shoreline of Yellowknife Bay are particularly striking (see Figs. 4 and 8A). Campbell (1948) worked out the movement on these faults in a study that led to the discovery of the extension of the ore-bearing Giant shear zone on the west side of the West Bay fault. The surface trace of this shear zone, appropriately known as the Campbell shear zone, lies under Great Slave Lake between Negus Point to beyond Kam Point. This was a very important geological-based mineral discovery — that is, not amenable to conventional surface exploration and prospecting.

Farther west of Yellowknife Bay, granitic rocks of the Western Plutonic Complex exhibit well-defined curvilinear features. Their form and distribution, vaguely resembling a long-legged spider, are unique in our experience. They appear to be unusual brittle fractures or joints, possibly related to doming or uplift of the Western Plutonic Complex and entirely distinct from the concentric structures of other granitic plutons.

Many structural lineaments are readily apparent on the Yellowknife–Hearne Lake SAR imagery (Figs. 4-7). We have outlined some of them in Figure 8. Masuoka *et al.* (1989:Fig. 8) also mapped brittle fractures from Seasat SAR images for the area east and west of Yellowknife. C-SAR, Seasat, Landsat and air photos all outline simple orthogonal and conjugate patterns typical of the study area and of the Canadian Shield in general. Explanations of the origin, distribution and characteristics of brittle fractures and their patterns have been the topic of much debate. Lowman *et al.* (in press) reviewed this debate and argued that most simple orthogonal or conjugate fractures in the Canadian Shield are brittle fractures of extensional origin (joint sets or normal faults). The scale of fracture systems ranges from less than 100 × 100 km for the Hearne (McKinley Point) dyke swarm to a length of several thousands of kilometres for the Mackenzie–Sudbury swarm, which stretches from Coronation Gulf on the arctic coast to the Grenville Front, south of Sudbury, Ontario (Fahrig and West, 1986). Many of the lineaments in the Yellowknife area are intruded by Precambrian diabase dykes. In this area, they are the 2200 millions year old, east-northeast-trending Dogrib or northeast- to north-northwest trending Indin dyke swarms, the 2000 million year, east-northeast Hearne (McKinley Point) swarm and the 1200 million year old, north-northwest-trending Mackenzie dyke swarm (Henderson, 1985; Fahrig and West, 1986). The Mackenzie and Hearne dykes may be magnetic and traceable on aeromagnetic maps. Diabase dykes may either be recessive or resistant and form obvious features or be comparable to host rocks and indistinguishable on radar images or topographic profiles. Many dykes occupy fractures and faults. On the other hand, many fractures and faults that are parallel dyke swarms are not intruded by diabase along any or some of their length.

Paleozoic - Cenozoic Tectonics

Evidence for post-Proterozoic movement or flexing along Precambrian fractures or lineaments has not been recognized in the Yellowknife area. However, experience in other areas shows that fracture lineament networks are selectively inherited from pre-existing regional fracture systems (Mollard, 1988; Fig. 9, modified from Shurr, 1982). It follows that these lineaments can be correlated with subsurface geological, hydrogeological and geophysical information. Shurr and Watkins (1989) have demonstrated that lineament zones marking Precambrian structural blocks are sites of Cretaceous and post-Cretaceous tectonism in three areas of the northern United States. Both ground water and natural gas seep through the sedimentary cover along these lineaments.

Paleozoic episodes of major uplift of the Precambrian block that forms the Boothia Arch and its buried extension are responsible for striking facies changes, karst development, faulting and folding, ground preparation and possibly channel ways for ore-bearing solutions in the Cornwallis Island Lead Zinc District (Kerr, 1977a,b).

In the Great Slave Lake area, structural flexing of the Precambrian Shield along the McDonald Fault fracture system has controlled the development of permeable secondary dolomite alteration, karsting and mineral deposits of the Pine Point Lead Zinc District (Skall, 1975). Webb (1986) recognized a north-northwesterly trending domal feature with local relief greater than 22 m in the back reef south trend of the Pine Point District. He interpreted the structure as the result of post-depositional, post-Presqu'ile (secondary) dolomitization flexing of the area and noted that it appears to correspond to a major basement feature recognizable on aeromagnetic maps. At the west end of the lake, block faulting, related to the Talthina Arch, cuts Paleozoic rocks as well as Precambrian basement. One can speculate that the Presqu'ile barrier may have been initiated by fluids capable of nourishing reef development and seeping up fractures, as recently described by Hovland (1990).

Neotectonics

Neotectonic joint systems are the most recent joint systems to form within a region subject to uplift and erosion (Hancock and Engelder, 1989) (see Fig. 10). Quaternary glaciation has resulted in considerable erosion, as evidenced by glaciated outcrops and absence of Paleozoic or Cenozoic rocks that overlie the Precambrian Shield to the west (Henderson, 1985).

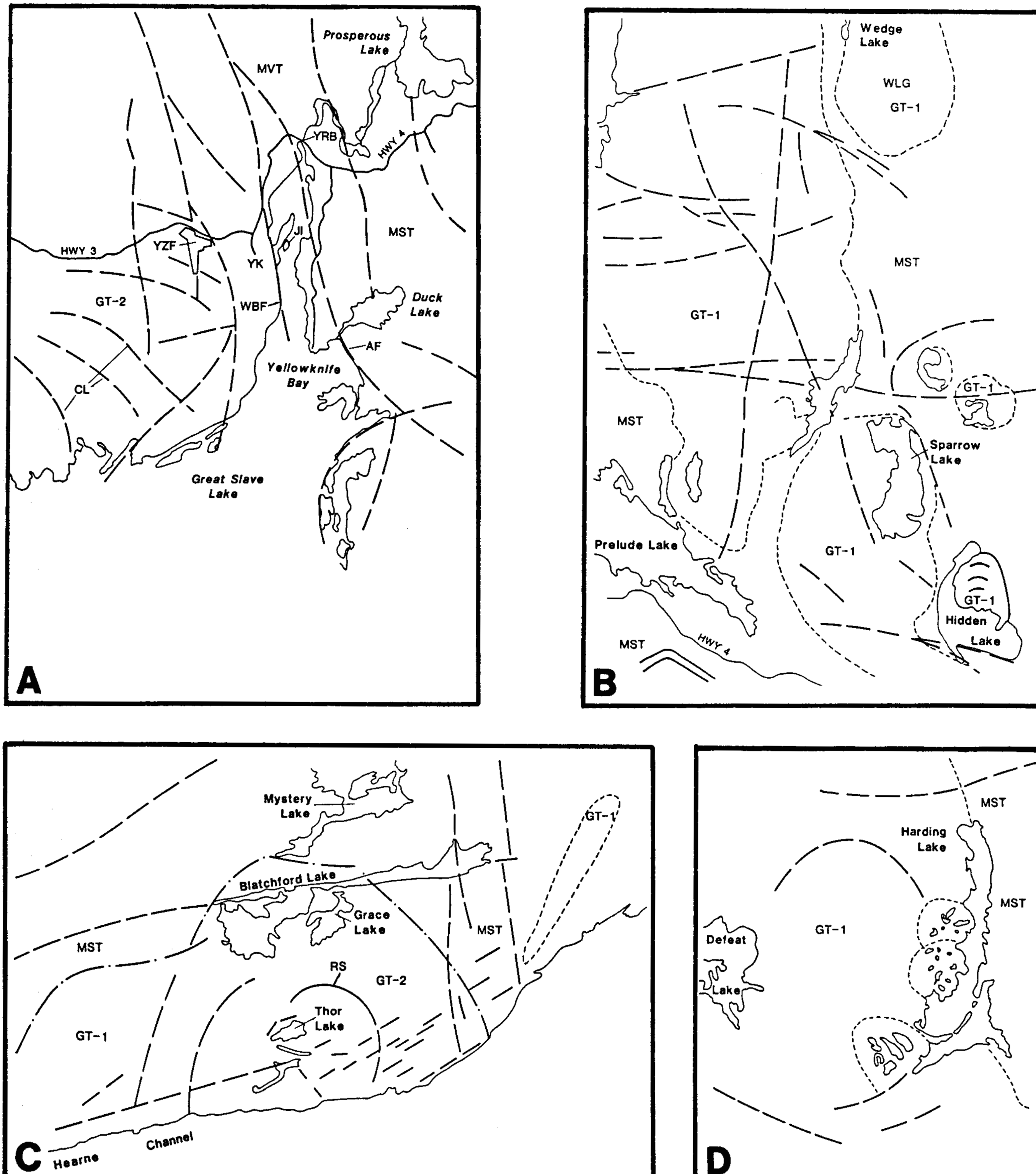

FIG. 8. Interpretation of lineaments: A – Yellowknife Bay, B – Prelude/Hidden Lake, C – Blatchford Lake, D – Defeat/Harding Lake. Abbreviations as in Figures 4–7.

Post-Wisconsin glaciation crustal uplift in the Yellowknife area is presently 4-5 mm per year (Peltier, 1986). Assuming this to be an average rate, the area has been uplifted a quarter of a metre since gold mining began 50 years ago, half a metre since the Klondike gold rush (100 years ago), more than a metre since Samuel Hearne and Alexander Mackenzie explored the area (200 years ago), or 40 m since the first native people arrived in the area 8000 years ago. Hasegawa (1988) reviewed evidence for neotectonics and inferred movements in Canada. He refers to studies of post-glacial faulting in bedrock in eastern Canada with millimetre-scale offsets of glacial striae along bedding planes, cleavages, joints or other high-angle pre-existing planes of weakness. The normals to the strikes of these faults point toward the Hudson Bay, the centre of maximum uplift, and are compatible with the ambient neotectonic stress field. Hasegawa's (1988:21) comment that "The large areal extent, relative inaccessibility, ground cover and relatively few surveys directed specifically to the search for post glacial faults are several of the reasons why post glacial faults have not been documented in much of the Canadian craton" is particularly appropriate for the Yellowknife area. This area has only sparse glacial deposits, but on the south side of Great Slave Lake lineaments in thick glacial overburden are both concordant and discordant with aeromagnetic (basement) lineaments.

Although we lack obvious geological evidence or proper stress measurements for proof of post-Precambrian and post-glacial or neotectonic movements, we do know that post-glacial uplift has taken and continues to take place in the Yellowknife area. We also have good circumstantial evidence from adjacent areas, such as the Pine Point area south of Great Slave Lake, where post-Precambrian and post-glacial lineaments tend to reflect aeromagnetic lineaments in the basement. A seismic survey by Clee *et al.* (1974) identified a near-surface low-velocity layer about 1 km thick that might correspond to a surface zone of fractures and joints that presumably become tighter and fewer at depth (Fig. 9B). Hasegawa (1988) points out that we should expect pronounced fault offsets and block movements in parts of the uplifted Canadian craton comparable to those observed in parts of Fennoscandia.

In view of this discussion, we feel it is reasonable to propose that the lineaments indicated on the Yellowknife radar imagery mainly reflect steeply dipping fractures and faults that may have been reactivated as extensional joint or fracture sets. Post-Precambrian and post-glacial lineaments may become active again with continued glacial uplift and have important implications for hydrology and geotechnical investigations.

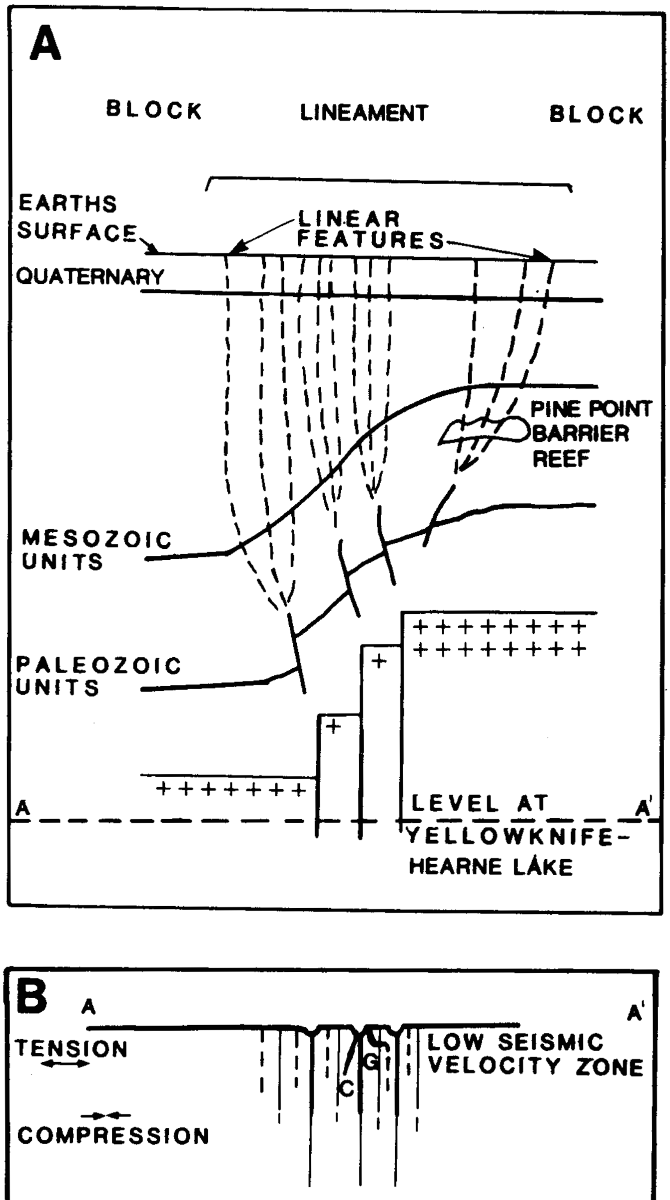

FIG. 9. A) Hypothetical cross-section showing lineaments as the surface expression of basement fault zones for the Northern Great Plains (modified from Shurr, 1982). B) Hypothetical cross-section showing faults and fractures in the Yellowknife–Hearne Lake area. C = Campbell shear zone (Con mine) and G = Giant Yellowknife shear zone.

COMPARISON OF RADAR IMAGERY WITH OTHER AREAL INFORMATION

The C-band airborne SAR used in our study is most readily comparable with L-band SAR obtained from the U.S. Seasat satellite (Masuoka *et al.*, 1989). The imagery is compatible, but Seasat's L-band radar was primarily designed to study waves on the ocean surface. The shorter wavelength of C-band radar permits more detail to be registered and is normally preferable for terrain analysis.

Landsat or thematic mapper and more recently SPOT satellite imagery are available in digital or hard copy form at scales that can be compared readily with radar imagery. These systems use visible and infrared wavelengths.

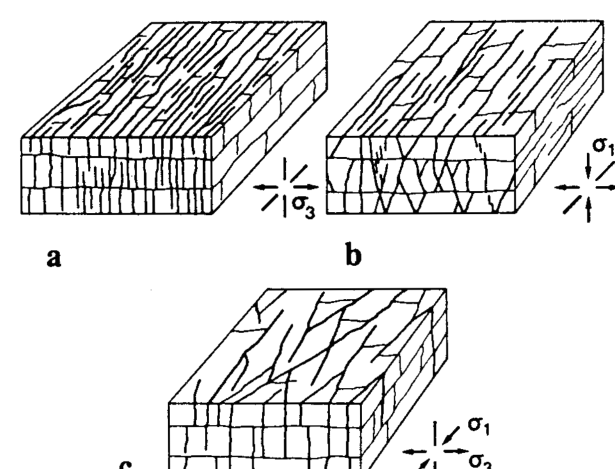

FIG. 10. Characteristic neotectonic joint systems. A) Single set of systematic vertical extension joints (heavy lines) linked by nonsystematic cross-joints (thin) lines. B) A spectrum of systematic joints (heavy lines) comprising vertical extension fractures and steep conjugate fractures enclosing a range of dihedral angles <45°. Two steep fracture directions are expressed by arrays of *en echelon* vertical joints. Nonsystematic joints (thin lines) link systematic joints. C) A spectrum of systematic joints (heavy lines) comprising vertical extension fractures and vertical conjugate fractures enclosing a range of dihedral angles <45°. Nonsystematic joints (thin lines) link systematic joints. σ_1, maximum effective principal stress; σ_3, minimum effective principal stress (from Hancock and Engelder, 1989).

Low sun angle thematic mapper imagery, sometimes called pseudo-radar, emphasizes relief or geological structures with more shadow than conventional air photos and is similar to airborne radar imagery in this regard.

Conventional black-and-white and colour air photographs for the Yellowknife area have obvious advantages when it comes to identifying small-scale features and those that have strong colour contrasts with their country rocks, e.g., white pegmatite dykes or large quartz veins and black diabase dykes, particularly in light-coloured granites. Air photographs can also be used to estimate the clarity of water in lakes and the discharge of sediment-laden rivers into standing bodies of water. Radar imagery has the advantage of clearly identifying subtle changes in topographic relief that may be due to recessive faults or fracture zones or resistant contacts or rock types. In the Yellowknife area, radar is clearly superior to air photographs in outlining drainage and standing water. This is particularly true for shallow, muddy lakes and rivers.

It is difficult and perhaps meaningless to compare various topographic maps with radar. Cost, availability and familiarity are important advantages of topographic maps.

Radar imagery and air photography are complements, not alternatives, to geology maps. In many areas, including Yellowknife, all three show excellent correlation.

Various geophysical maps, aeromagnetic, gravity and radioactivity or gamma ray, mainly reflect complex geophysical signatures of subsurface features that may or may not be identifiable at the surface. Aeromagnetic maps are the best for comparison with surface geology. Linear displacements in magnetic patterns typically reflect basement faults, and high values of magnetic field commonly outline diabase dykes and certain granite and/or carbonatite intrusions, such as the Blatchford Lake area.

CONCLUSIONS

C-band SAR imagery of the Yellowknife–Hearne Lake area effectively reflects the physiography of the area by means of tonal changes (Table 1). Because surficial deposits and vegetation are sparse, topography is controlled to a large degree by bedrock geology. Structural lineaments due to faults and brittle fractures at an angle to the radar look direction are clearly outlined and several terrain types based on the erosional characteristics of lithologies can be identified. Radar imagery also provides an accurate picture of drainage and water resources. Certain cultural features, such as urban areas, airports, bridges, etc., can be identified with minimal experience.

Radar lineament analysis was successful in mapping north-northwest strike slip faults that displace important gold-bearing shear zones in Yellowknife Bay, east-northeast block faulting with south-trending down stepping in the eastern Blatchford Lake Complex and unusual curvilinear features in the Western Plutonic Complex. Post-glacial or neotectonic activity on many structural lineaments is possible, if not probable.

Radar image interpretation improves with experience, effort and knowledge of the terrain and geology. It can be complementary or an alternative to air photo interpretation and is most useful before and during field mapping.

Future plans of the authors include interpretation of imagery of the same area with a different look direction and field checks to some of the more interesting radar features identified on the radar imagery.

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REFERENCES

BARAGAR, W.R.A., and McGLYNN, J.C. 1976. Early Archean basement in the Canadian Shield: A review of the evidence. Geological Survey of Canada, Paper 76-14.

BIRKETT, T., SINCLAIR, D., and RICHARDSON, D. 1989. Gravity interpretation of the Blatchford Lake Intrusive Complex. In: Mining exploration and geological investigations — 1989. Yellowknife: Indian and Northern Affairs Canada. 27-28.

CAMPBELL, N. 1948. West Bay Fault. In: Structural geology of Canadian ore deposits. Canadian Institute of Mining and Metallurgy, Jubilee vol.:244-259.

CLEE, T.E., BARR, K.G., and BERRY, M.J. 1974. Fine structure of the crust near Yellowknife. Canadian Journal of Earth Sciences 11:1534-1549.

DAVIDSON, A. 1981. Petrochemistry of the Blatchford Lake complex, District of Mackenzie (85 I/1,2). Geological Survey of Canada, District of Mackenzie, Open File 764.

DRURY, S.A. 1977. Structures induced by granite diapirs in the Archean greenstone belt at Yellowknife, NWT: Implications for Archean geotectonics. Journal of Geology 85:345-358

______. 1987. Radar remote sensing. In: Image interpretation in geology. London: Allen & Unwin. 165-174.

FABBRI, A.G., KUSHIGBOR, C.A., WONG, L., BAKER, A.S., and ROSCOE, S.M. 1989. Integration of remotely ranged and ancillary geological data for assessing mineral resources in the Bathurst Inlet area, NWT, Canada. Proceedings of the 21st Application of Computers and Operations Research in the Mineral Industry (APCOM), Las Vegas, Nevada, 27 Feb.-2 Mar. 1989. Society of Mining Engineers Inc. 1109-1120.

FAHRIG, W.F., and WEST, T.D. 1986. Diabase dyke swarms of the Canadian Shield. Geological Survey of Canada Map 1627A.

FYSON, W.K. 1982. Complex evolution of folds and cleavages in Archean rocks, Yellowknife, NWT. Canadian Journal of Earth Sciences 19:878-893.

______. 1984a. Fold and cleavage patterns in Archean metasediments of the Yellowknife domain, Slave Province. In: Kroner, A., ed. Precambrian tectonics illustrated. Amsterdam: Elsevier. 281-293.

______. 1984b. Basement-controlled structural fronts forming an apparent major refold pattern in the Yellowknife domain, Slave Province. Canadian Journal of Earth Sciences 21:822-828.

FYSON, W.K., and HELMSTAEDT, H. 1988. Structural patterns and tectonic evolution of supracrustal domains in the Archean Slave Province, Canada. Canadian Journal of Earth Science 25(2):301-315.

HANCOCK, P.L., and ENGELDER, T. 1989. Neotectonic joints. Geological Society of America Bulletin 101:1197-1208.

HASEGAWA, H.S. 1988. Neotectonics and inferred movements in Canada. Bulletin Geological Society Finland 60(Part 1):3-25.

HELMSTAEDT, H., and PADGHAM, W.A. 1986. A new look at the stratigraphy of the Yellowknife Supergroup at Yellowknife, NWT, implications for the age of gold-bearing shear zones and Archean basin evolution. Canadian Journal of Earth Sciences 23:454-475.

HELMSTAEDT, H., PADGHAM, W.A., and BROPHY, J.A. 1986. Multiple dykes in Lower Kam Group, Yellowknife greenstone belt-evidence for Archean sea floor spreading? Geology 14:562-566.

HENDERSON, J.B. 1981. Archean basin evolution in the Slave Province, Canada. In: Kroner, A., ed. Plate tectonics in the Precambrian. Amsterdam: Elsevier. 213-235.

______. 1985. Geology of the Yellowknife–Hearne Lake area, District of Mackenzie: A segment across an Archean basin. Geological Survey of Canada Memoir 414.

HENDERSON, J.F. 1941. Beaulieu River, District of Mackenzie, Northwest Territories. Geological Survey of Canada Map 581A, with marginal notes.

HOVLAND, M. 1990. Do carbonate reefs form due to fluid seepage? Terra Nova 2:8-18.

JOLLIFFE, A.W. 1942. Yellowknife Bay, Northwest Territories. Geological Survey of Canada Map 709A.

______. 1946. Prosperous Lake, District of Mackenzie, Northwest Territories. Geological Survey of Canada Map 868A.

KERR, J.W. 1977a. Cornwallis Fold belt and the mechanism of basement uplift. Canadian Journal of Earth Science 14(6):1374-1401.

______. 1977b. Cornwallis lead-zinc districts Mississippi Valley-type deposits controlled by stratigraphy and tectonics. Canadian Journal of Earth Sciences 14(6):1402-1426.

KUSKY, T.M. 1989. Accretion of the Archean Slave Province. Geology 17:63-67.

LAMBERT, M.B. 1988. Cameron River and Beaulieu River volcanic belts of the Archean Yellowknife Supergroup, District of Mackenzie, Northwest Territories. Geological Survey of Canada Bulletin 382. 145 p.

LASMANIS, R. 1978. Lithium resources in the Yellowknife area, Northwest Territories, Canada. Energy 3:399-407.

LIVINGSTON, C.E., GRAY, A.C., HAWKINS, R.K., OLSEN, J.G., and HALBERTSMAN, J.G. 1987. C-band airborne radar: System description and test results. Proceedings Eleventh Canadian Symposium on Remote Sensing, Waterloo, Ontario, 1987. 503-518.

LOWMAN, P.D., Jr., WHITING, P.J., SHORT, N.M., LOHMANN, A.M., and LEE, G. In press. Fracture patterns on the Canadian Shield: A lineament study with Landsat and orbital radar imagery. Proceedings of the Seventh International Conference on Basement Tectonics, August 1987, Kingston, Ontario.

MASUOKA, P.M., LOWMAN, P.D., BLODGET, H.W., GARVIN, J.B., GRAHAM, D., HARRIS, J., KUSKY, T., SINGHROY, V.H., and SLANEY, V.R. 1989. Shuttle Imaging Radar (SIR-B) investigations of the Canadian Shield. Summary report. Technical Papers of the 1989 ASPRS Convention 3:425-437.

MOLLARD, J.D. 1988. First R.M. Hardy Memorial Lecture: Fracture lineament research and applications on the western Canadian plains. Canadian Geotechnical Journal 25:749-767.

MUSSAKOWSKI, R., TROWELL, N.F., SAGE, R.P., and HEATHER, K.B. 1989. Digital integration of remote sensing and geoscience data for the Goudreau-Lochalsh study area, Michipicoten greenstone belt, Wawa, Ontario. Proceedings Seventh Thematic Conference on Remote Sensing for Exploration Geology, Calgary, Alberta, Canada, 2-6 October 1989. 1051-1065.

PADGHAM, W.A. 1986. Turbidite-hosted gold-quartz veins in the Slave Structural Province, NWT. In: Keppie, D.J., Boyle, R.W., and Haynes, S.J., eds. Turbidite hosted gold deposits. Geological Association of Canada Special Paper 32:119-134.

PELTIER, W.R. 1986. Deglaciation-induced vertical motion of the North American continent and transient lower mantle rheology. Journal for Geophysical Research 91:9099-9123.

SABINS, F.F. 1987. Radar images. In: Remote sensing — Principles and interpretation. 2nd ed. New York: W.H. Truman & Co. 177-234.

SHURR, G.W. 1982. Geological significance of lineaments interpreted from Landsat images near the northern Black Hills. In: Christopher, J.E., and Kaldi, J., eds. Fourth International Williston Basin Symposium. Saskatchewan Geological Society Special Publ. No. 6:313-320.

SHURR, G.W., and WATKINS, I.W. 1989. Basement blocks, tectonics, and fluid movement — "Seeping" through the sedimentary cover. Proceedings Seventh Thematic Conference on Remote Sensing for Exploration Geology, Calgary, Alberta, Canada, 2-6 October 1989, 1:501-517.

SKALL, H. 1975. The paleoenvironment of the Pine Point lead-zinc district. Economic Geology 70:22-45.

SLANEY, V.R., and MISRA, K. 1988. Radar studies of the Sudbury Basin (Abs.). In: Scientific Drilling: The Sudbury Structure, Proceedings of a workshop held on 6 and 7 October 1988. Canadian Continental Drilling Program Report 88-2:16.

STOKES, T.R., ZENTILLI, M., and CULSHAW, N. 1989. A structural and lithologic model for the formation of gold bearing quartz breccias at Gordon Lake. N.W.T. NWT Geology Division. Open File Report EGS 1989-17. 33 p. plus map.

TREVETT, J.W. 1986. Geological interpretation. In: Imaging radar for resources surveys. New York: Chapman and Hall. 139-160.

TRUEMAN, D.L., PEDERSEN, J.C., DE ST. JORRE, L., and SMITH, D.G.W. 1988. The Thor Lake rare-metal deposits, Northwest Territories. In: Taylor, R.P., and Strong, D.F., eds. Recent advances in the geology of granite related deposits. Montreal: The Canadian Institute of Mining and Metallurgy. Special vol. 39:280-290.

WEBB, R.C. 1986. Localization of prismatic orebodies by stratigraphic/structural controls, South Trend, Pine Point Lead Zinc Property, Northwest Territories, Canada. M.Sc. thesis, University of Waterloo, Waterloo, Ontario.