Bulletin 45

POLYPHASE DEFORMATION

In the Canadian Shield of Northeastern Alberta

C.W. Langenberg

Alberta
RESEARCH COUNCIL
Natural Resources Division

Alberta
Geological Survey

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Acknowledgments

This study is based on data collected under the leadership of Dr. J.D. Godfrey. He suggested the study and I would like to express my appreciation for his encouragement and stimulating discussions. Dr. J. Ramsden helped with the computing. Eldorado Nuclear Ltd. supplied *in situ* stress measurements. Dr. E.A. Babcock read and critized a first draft on the sections dealing with joints. Drs. H.A.K. Charlesworth and G.D. Mossop read the manuscript.

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Preface

The Canadian Shield of northeastern Alberta has considerable exploration and development potential in economic mineral deposits. For this reason, the Alberta Geological Survey has conducted extensive geological studies in the region since the mid 1950's, and is currently in the process of publishing a series of synthesis reports. This Bulletin deals with the structural geology of the terrain. By addressing the geometry of the deformed rocks and their fracture patterns, it provides a basis for the establishment of exploration targets and a rationale for understanding geotechnical behaviour.

Grant Mossop,
October, 1983

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Abstract

The Canadian Shield of northeastern Alberta, within the Athabasca Mobile Belt, consists largely of reworked Archean basement. Two generations of structures can be distinguished in the granite gneisses and intercalated high-grade metasediments of the basement gneiss complex, which has been shown to be Archean by radiometric dating. The older generation (D_1), characterized by tight to isoclinal folds in the foliation, is assigned to the Kenoran orogeny. The younger (D_2) folds are more open, and have affected D_1 axial traces. In some areas, D_2 folds form parts of domes within the gneisses.

Most granitoid masses give radiometric ages of about 1900 Ma and show a dome and basin geometry. These domes are generally immature diapirs and are correlated with D_2 structures in the gneisses. The predominance of D_2 structures in the granitoids is the basis for assigning these structures to the Aphebian. The environment of deformation, indicated by metamorphic minerals within the enclosed high-grade metasediments, shows temperatures of 740 ± 30 °C and pressures of 5 ± 0.7 kbar. Some of the D_2 folds fit a conical fold model. Post D_2, large-scale fault zones are accompanied by extensive mylonitization. Jointing is related to regional stress fields.

Introduction

This bulletin forms part of a series of Alberta Research Council publications on the geology of the Canadian Shield of northeastern Alberta. Mapping began in 1957 and ended in 1975. District geological maps have been published for parts of the area (see section on previous work). The remaining districts will be covered in future Alberta Research Council reports.

This study summarizes the structural geology of the exposed Canadian Shield of northeastern Alberta. The successive phases of deformation are put in a temporal framework, based on geochronological studies.

Location and accessibility

The study area is located in northeastern Alberta, Canada, between latitudes 58°30 and 60°N and longitudes 110° and 112°W. The area forms parts of the Fitzgerald (NTS 74M) and Fort Chipewyan (NTS 74L) map sheets (see figure 1).

Regularly scheduled flights to both Fort Smith (Northwest Territories) and Fort Chipewyan provide access to the area.

Methodology

A structural geological map of the area on a scale of 1:250 000 is presented (figure 1, in pocket). This map is based on both published and unpublished district maps and on structural analyses of selected study areas. The computer-based numerical methods described by Langenberg and Ramsden (1980) were applied to these areas. The structures found in these areas are considered representative of structures elsewhere in this part of the Canadian Shield. Cross-sections through the selected areas are presented. The computer-based techniques are more accurate and faster to implement than the traditional graphical methods. The orientation diagrams of joints measured in the field are compared with the orientation of joints in adjacent areas.

Previous work

In 1957, the Alberta Research Council began systematic mapping of the Precambrian Shield in northeastern Alberta, and published several district maps in this series (Godfrey, 1961, 1963, 1966, 1970, 1980a, 1980b; Godfrey and Peikert, 1963, 1964). Geochronological studies have been published on those portions of the Shield initially mapped by the Alberta Research Council (Baadsgaard and Godfrey, 1967, 1972; Kuo, 1972; Day, 1975). Godfrey (1958b) reported mineral showings in the Andrew, Waugh and Johnson Lakes areas. Godfrey (1958a) also made a structural interpretation of the Shield in Alberta, north of Lake Athabasca, based on stereoscopic vertical air photographs.

In 1959, the Geological Survey of Canada conducted a reconnaissance geological survey of the Precambrian Shield in Alberta north of Lake Athabasca and published a map with marginal notes (Riley, 1960).

Peikert (1961, 1963) studied the petrogenesis of certain granitoid rocks in the Colin Lake area. Watanabe (1961) described metasediments of the Waugh Lake area and later (1965), cataclastic rocks of the Charles Lake area. Klewchuk (1972) reported on the petrogenesis of several granitoid rocks from the Fort Chipewyan district.

Under the auspices of the Geological Survey of Canada, in 1977 the Alberta Research Council was invited to participate in a project to compile a metamorphic map of the Canadian Shield (GSC Map 1475A).

The symposium volume accompanying the metamorphic map includes a paper on the metamorphic history of the Shield in northeastern Alberta (Godfrey and Langenberg, 1978). Langenberg and Nielsen (1982) prepared a more detailed account of the metamorphic history of the area. Langenberg and Ramsden (1980) discuss the geometry of macroscopic folds in the Tulip Lake and Hooker Lake areas. Another recent publication (Nielsen *et al.,* 1981) puts the crustal evolution of the area into a regional framework.

General geology

The Precambrian shield of northeastern Alberta consists of massive to foliated granitoids, granite gneisses and metasediments (figure 2). This Shield, which forms part of the Churchill Structural Province, is situated in the Athabasca Mobile Belt (Burwash and Culbert, 1976). The geological history involves sedimentation, deformation, metamorphism and ultrametamorphism, accompanied by remobilization. These processes have operated during different orogenic periods, resulting in the formation of complex polymetamorphic rocks. Field contact relationships and bulk compositions suggest that the migmatitic granitic gneisses and high-grade metasediments were parent materials for several of the granitoid rocks (for example, see Klewchuk, 1972). Thus, the granitoids represent Archean basement remobilized during the Aphebian (see also Davidson, 1972). Lewry and Sibbald (1980) discuss the thermotectonic evolution in adjacent parts of Saskatchewan.

Geochronological studies of rocks from the area (Baadsgaard and Godfrey, 1967, 1972) provide further evidence of multiple orogenic cycles in northeastern Alberta. This latter work deals with the Charles Lake, Andrew Lake and Colin Lake districts, and identifies two distinct orogenic cycles. Rb-Sr whole rock isochrons on pegmatites within granitoids, gneisses and metasediments in the Charles Lake area give ages of about 2500 Ma. Thus, they are considered part of an Archean basement gneiss complex. The low initial $^{87}Sr/^{86}Sr$ ratio (0.7030) of the pegmatites points to the presence of I-type granitoids. This initial Sr ratio is also within the limits for their derivation from mantle-like source material.

Rb and Sr determinations on Colin Lake Granitoids plot on a well-defined isochron with $T = 1893 \pm 6$ Ma. A high initial $^{87}Sr/^{86}Sr$ ratio of 0.7083 ± 0.0002 indicates derivation of these rocks by anatexis of pre-existing sedimentary rocks (Baadsgaard and Godfrey, 1972, p. 870). The immediate parent materials for the Colin Lake Granitoids are probably the nearby Archean granite gneisses and high-grade metasedimentary rocks. The Slave Granitoids give an age of 1938 ± 29 Ma (Nielsen *et al.,* 1981). Most other granitoids (Wylie Lake, Arch Lake, Thesis Lake and minor Granitoids) also show Aphebian ages (Baadsgaard, pers. comm.).

K-Ar determinations on muscovite, biotite and hornblende give a narrow distribution of ages. The average age of mica from many rock units is 1790 ± 40 Ma, which indicates that the K-Ar dates for all rocks within the region were effectively reset as a consequence of the Hudsonian orogeny. Thus, two Precambrian orogenic cycles are firmly established for the Shield rocks of northeastern Alberta.

Two distinct cycles of metamorphism (Langenberg and Nielsen, 1982) represent these cycles. The Archean cycle shows high-pressure granulite facies conditions ($P = 7.5 \pm 2$ kbar, $T = 900 \pm 100$°C). The Aphebian cycle shows a three-stage cooling sequence from moderate-pressure granulite facies ($P = 5.0 \pm 0.7$ kbar, $T = 740 \pm 30$ °C), through low-pressure amphibolite facies ($P = 3.0 \pm 0.3$ kbar, $T = 555 \pm 55$ °C), to greenschist facies ($P \approx 2$ kbar, $T = 260 \pm 35$ °C) conditions.

Low-grade metasedimentary rocks, accompanied by metavolcanics in the Waugh Lake area (southeast of

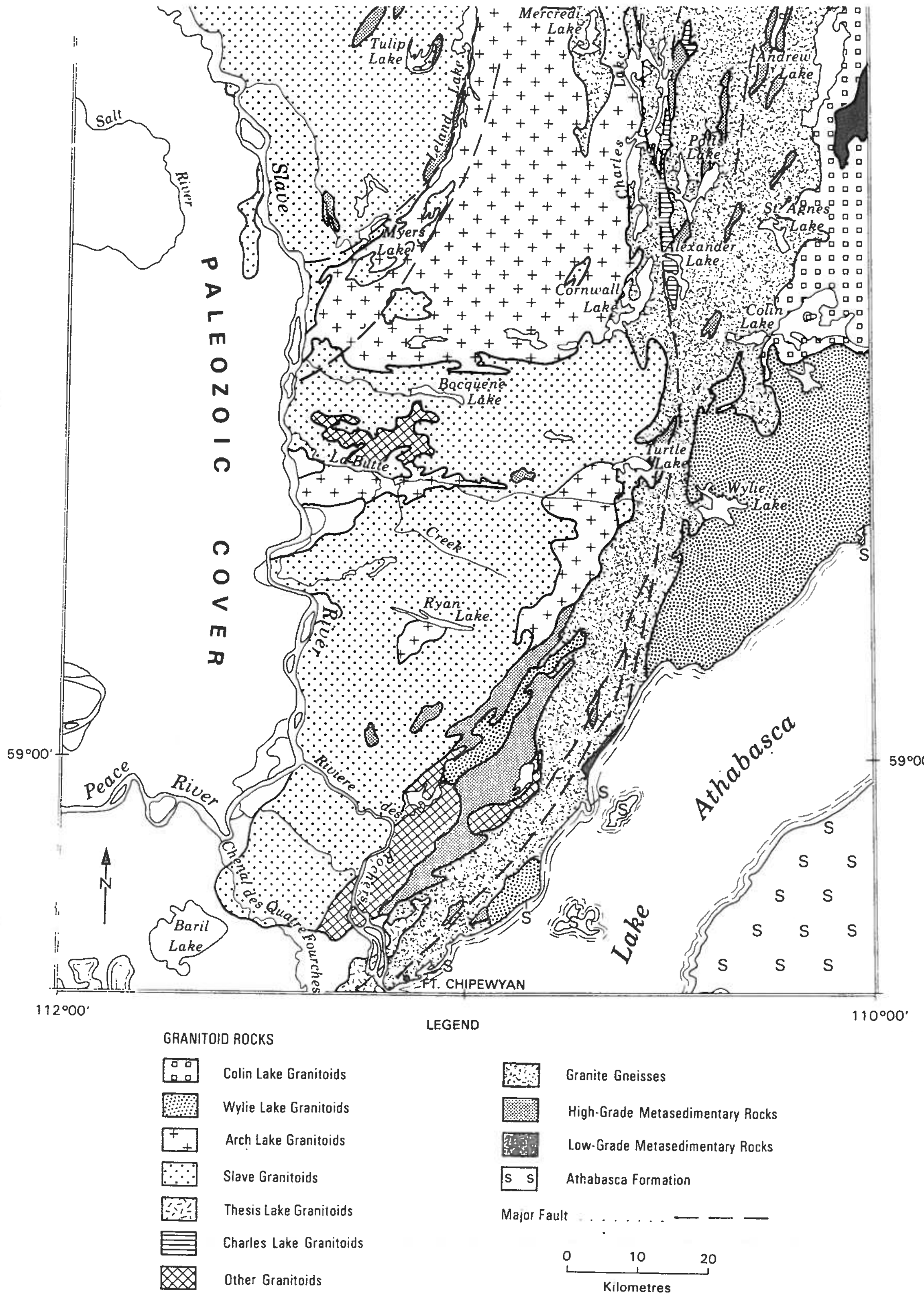

Figure 2. Simplified geological map of the Precambrian Shield of northeastern Alberta, north of Lake Athabasca.

Andrew Lake), show primary sedimentary and igneous structures respectively. An unconformity is assumed between the low-grade metasedimentary rocks and the Archean granite gneisses with high-grade metasedimentary rocks. The age relationship between the low-grade metasedimentary rocks and the nearby Colin Lake Granitoids is uncertain. Peikert (1961, 1963) postulates that the Colin Lake Granitoids formed by anatexis of the low-grade metasedimentary rocks. This explanation, however, seems improbable, because temperatures in the greenschist facies are too low for partial melting to occur (Koster and Baadsgaard, 1970). Therefore, the high-grade metasedimentary rocks and granite gneisses are more likely parent materials for these and other nearby granitoid bodies. An unconformity is also required to exist between the low-grade metasediments and the Colin Lake Granitoids. A K-Ar age of 1760 Ma for biotite from the low-grade prograde greenschist facies metasediments (Baadsgaard and Godfrey, 1972) correlates with the retrograde greenschist facies found elsewhere in the area.

Major faults affect most of the rock units and are younger than the macroscopic fold structures in the granitoids. These faults are expressed as shear zones characterized by mylonites (Watanabe, 1965). Retrograde greenschist facies minerals in the mylonitic zones suggest a late Aphebian age for this large-scale faulting. Breccias along some transverse faults may indicate still younger fault movements at higher crustal levels.

Continental conditions prevailed during deposition of the Helikian Athabasca Formation, which lies unconformably on the older crystalline basement rocks.

Glacial scouring during the Pleistocene has left numerous fresh outcrops, which greatly facilitate geologic studies in the area.

Structural analysis

The structural geological map (figure 1, in pocket) is obtained by transferring orientations of structural elements and structural trend lines from published and unpublished district maps (2 inches to 1 mile scale) to a 1:250 000 base map. The district maps contain many structural elements measured in the field. The smaller scale map has only a selection of these measurements. To help select the measurements and to obtain models for the geometry of the large-scale structures, a more detailed analysis of the structural elements is conducted of specific study areas. In the field, structural elements are measured at stations from 100 to 200 m apart along parallel traverses spaced at 1.0 to 1.5 km. A one mile (1.6 km) grid, based on the township system, is chosen to divide each selected area into subareas for data reduction. The only mesoscopic structures used are foliations; no mesoscopic folds nor mineral lineations were encountered in the granitoids. Only one foliation is present at each outcrop and it is not always well developed. Thin sections show that the foliation is formed by elongated lenses of platy quartz, flattened feldspars and biotite. The textures indicate a dynamometamorphic origin for the foliation.

The foliation measurements within each square mile subarea form a data-set and coordinates for the data-set are obtained from the appropriate traverse. Ground elevations are assumed to be constant over the study area. Each foliation measurement is considered a unit vector oriented normal to the foliation. This line can be described in terms of three direction-cosines, given by the components of the line along three mutually perpendicular axes, usually taken as north, east and down. With reference to this three-dimensional system, the ith of a total of p observations will have components (l_i, m_i, n_i). A 3×3 matrix of the sums of squares and products of (l_i, m_i, n_i) in a particular subarea can be formed:

$$T = \begin{bmatrix} \Sigma l_i^2 & \Sigma l_i m_i & \Sigma l_i n_i \\ \Sigma m_i l_i & \Sigma m_i^2 & \Sigma m_i n_i \\ \Sigma n_i l_i & \Sigma n_i m_i & \Sigma n_i^2 \end{bmatrix}$$

It can be shown (see, for example, Charlesworth *et al.*, 1976; Mardia, 1972) that the eigenvalues and eigenvectors of the matrix T describe the distribution of foliation orientations in the subarea. One large and two very small eigenvalues (unimodal distribution) indicate that the measurements are clustered about a mean whose orientation is given by the eigenvector associated with the largest eigenvalue. One very small and two large eigenvalues (girdle distribution) indicate that folding is present in the subarea. The fold axis of the subarea can be estimated from the eigenvector associated with the smallest eigenvalue. Based on these eigenvalues, the subareas are classified into those with or without folding.

Modal foliations

For *subareas that do not show folding,* the mean foliation orientations are used in the remainder of the analysis. The individual measurements in these subareas can be considered as repeated measurements of the foliations and a concentration parameter K of the Fisher distribution can be calculated. This parameter estimates measurement errors and also indicates roughness of the folded surfaces. The roughness may include: roughness of the folded surface in a subarea, and possibly folding in a subarea not detected in the first part of the analysis. K decreases with increasing error and roughness and is used in statistical tests to establish domains (Charlesworth *et al.,* 1976). For *subareas with considerable folding,* the most commonly occurring orientation is selected, which in many cases can be identified as the maxima on stereo-plots (Whitten, 1966, p. 49). These selected measurements are modal limbs and the selection results in smoothing of folded surfaces. This smoothing is acceptable because the irregularities are much smaller in scale than the structures of interest.

These procedures reduce the number of measurements to be manipulated, and the modal foliation orientations obtained are used in the analysis of the selected study areas.

Establishing domains

Statistical tests involving modal foliations can be used to subdivide the selected study areas into cylindrical domains (Kelker and Langenberg, 1976; Charlesworth *et al.,* 1976). The concentration parameter K in the areas studied generally has a low value, so the test for co-polarity is not sensitive and large areas can be accepted as cylindrical domains. In such cases, the F-test for co-axiality is more sensitive and aids in subdividing the study areas into domains.

Langenberg *et al.* (1977) outline a procedure to position precisely the boundaries between domains. The angles between the normal to the measured surface and the fold axes of provisional domains at a data station are compared. The method also enables identification of spurious data (possibly resulting from large measurement errors) that can be subsequently eliminated. Once a domain has been established, its fold axis is estimated from the eigenvector associated with the minimum eigenvalue of the matrix T formed from the modal foliations. The normalized minimum eigenvalues (minimum eigenvalue divided by number of data stations) give an estimate of the degree of cylindricity. The best cylindricity is generally indicated by the smallest normalized minimum eigenvalue.

The geometry of domal structures can approach conical shapes. Diapiric domes are found in the area and the domains are tested for conicity. Kelker and Langenberg (1982) describe the procedure for this statistical testing. An interactive least squares technique is used to determine the best-fitting cone axis. The half apical cone angle is calculated from the orientation of the cone axis. Several statistical tests exist that determine if a fold better fits the conical rather than the cylindrical model. A normal distribution test based on the standard deviation of the cone angle is used. When the conical model is accepted, a goodness-of-fit test shows if it is an ideal conical fold. For details of the testing procedure, see Kelker and Langenberg (1982).

Sections

Where cylindrical domains have been established, structural sections can be obtained by the method of down-plunge projection. Data stations are projected from the topographic surface, parallel to the fold axis, onto the plane of the section. These projections can be obtained using a computer as explained by Charlesworth *et al.* (1976).

Composite sections of adjacent domains can be obtained if one domain is rotated so that its fold axis assumes the same orientation as the fold axis of the other domain (Langenberg *et al.,* 1977).

Sections of domains that show conical folding can be expected to be inaccurate, because the shape of the fold will change in the direction of the fold axis. These inaccuracies are, however, reduced if the distances of projections parallel to the fold axes are small — the method of down-plunge projection is particularly applicable if the domains are relatively narrow in the direction of the fold axis. It should be remembered that the classical method of preparing geological cross-sections, whereby foliation orientations are projected parallel to the strike onto the plane of section, is more inaccurate.

Block diagrams

Horizontal and vertical sections are used to construct block diagrams of cylindrical domains. The projections are performed numerically, involving the following steps:

1. Data stations and foliations are projected down-plunge on the sides of the block.
2. The two-dimensional coordinates in these planes are referred to the three-dimensional coordinate system north, east and vertical.
3. These coordinates are referred to the mutually perpendicular axes X′, Y′ and Z′, where Z′ is viewing direction and X′ horizontal.
4. The coordinates x′ and y′ are the coordinates for the orthographic projection.
5. For a perspective projection, an observer's position is chosen along the viewing direction and the coordinates are transformed accordingly.
6. The block diagram is plotted by the computer. Contacts between rock units are drawn by hand.

Langenberg and Ramsden (1980) describe this method.

Joints

One or two (rarely three) major joint directions were measured in many outcrops. The major joint directions in each outcrop are defined as the most persistent joint directions present. Most of these joints are vertical to steeply dipping. Some near-horizontal joints are observed, but because the Precambrian outcrop is flat, they are not represented in our sampling. The vertical and near-vertical joint measurements are grouped by township and can be displayed in rose diagrams of the strike orientations. In conventional rose diagrams, percentages of occurrences in 10° azimuthal intervals are represented. These diagrams are circular histograms. In this study, the rose diagrams are smoothed by a technique developed by Ramsden (1975). Instead of representing every measurement as a point distribution, a weighting factor is used for each measurement. The weighting function is taken to be the von Mises density function, which is proportional to exp ($k \cos \theta$) (Mardia, 1972, p. 57), where k is the von Mises precision parameter and θ is the angle between any direction and the observed orientation. Every joint orientation is now represented by a bell-shaped curve.

Adding together all the bell-shaped curves generates a smoothed rose diagram. These procedures are easily performed by computer. Figures 30 and 31 contain examples of computer-plotted rose diagrams. The circle in these plots represents a uniform distribution (0.55 percent of the observations per 1 degree interval).

In all plots a concentration parameter k of 50 is used. This is a reasonable estimate if one realizes that a concentration parameter $k = 50$ implies an angular deviation of 8.1° (see Table B in Batschelet, 1965). The angular deviation behaves similarly to the familiar standard deviation. Consequently, a concentration parameter of 50 means that, if repeated measurements were performed, 95 percent of the measurements would fall in a 32 degree interval with the mean in the middle. This is a reasonable estimate of the amount of roughness and measurement error of individual joints.

The smoothed rose diagrams are considered improvements over the conventional rose diagrams.

Selected study areas

Six areas were selected for a detailed analysis. The locations of the areas are indicated on figure 3 and are designated by a large lake in the area: Tulip Lake, Hooker Lake, Arch Lake, Disappointment Lake, Wylie Lake and St. Agnes Lake areas. The first five areas describe the macroscopic structures found within Aphebian Granitoids. The St. Agnes Lake area is representative of macroscopic structures in the Archean basement gneiss complex. A larger area of the granitoids was studied because they occupy a larger area than the basement gneiss complex. The basement gneiss complex exhibits abundant mesoscopic folding, which is absent in the Aphebian granitoids.

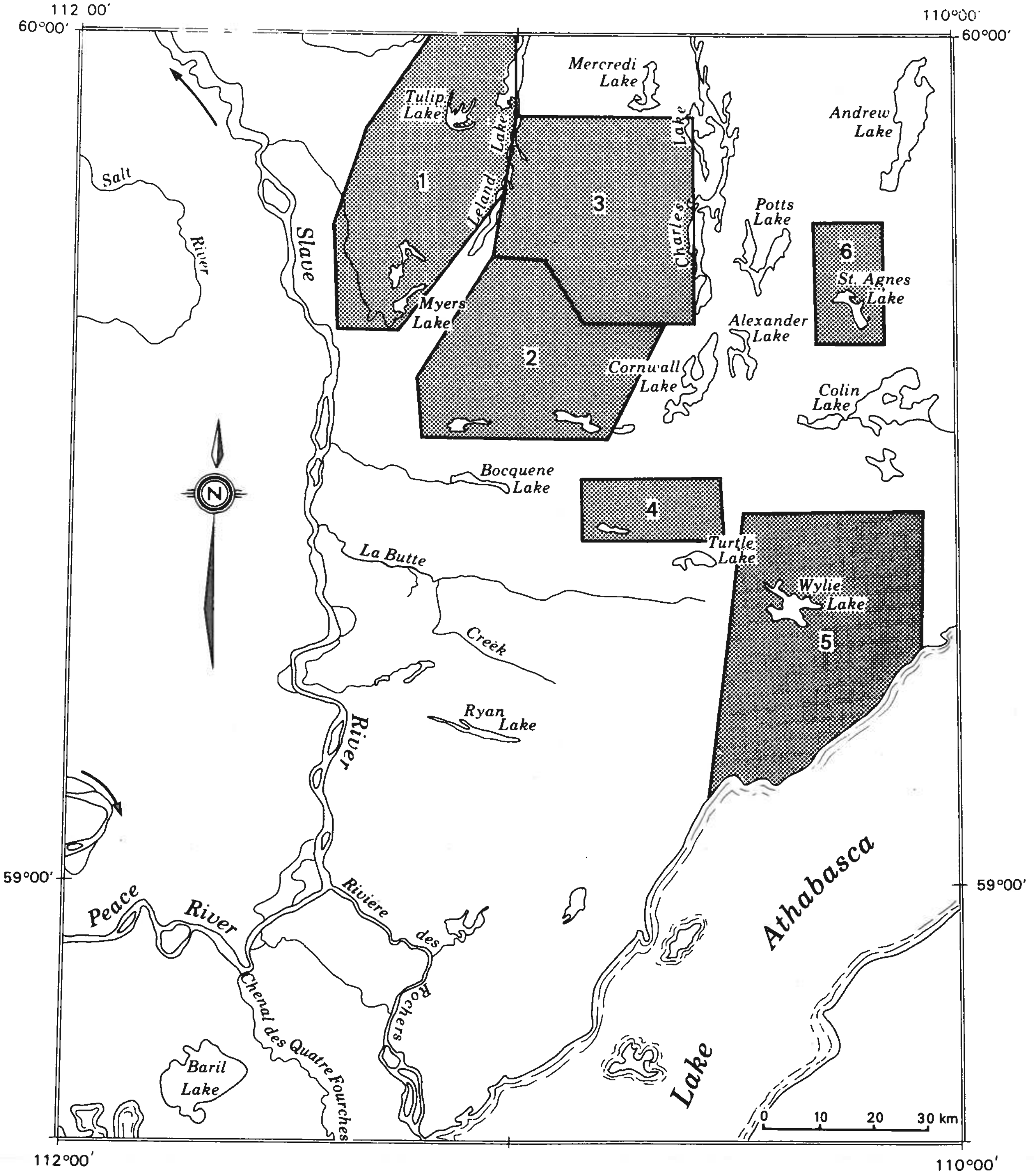

Figure 3. Location of selected areas 1—Tulip Lake area; 2—Hooker Lake area; 3—Arch Lake area; 4—Disappointment Lake area; 5—Wylie Lake area; 6—St. Agnes Lake area.

Tulip Lake area

The Tulip Lake area is underlain by foliated Slave Granitoids (figures 1 and 4), which define a dome. Inclusions of banded quartzo-feldspathic rocks ranging in size from hand specimens to mappable areas occur in the Slave Granitoids (Godfrey and Langenberg, in prep. a and b). They are interpreted as metasedimentary rocks that define a ghost stratigraphy. High-grade metamorphic minerals are found both in the metasediments and the enclosing granitoid rocks, but in the latter in lesser proportions. The only mappable lithological contacts are those between Slave Granitoids and metasediments. The Slave Granitoids have been arbitrarily divided into nine concentrically arranged units, based on structural form lines drawn along the strikes of modal foliations and the contacts of metasedimentary rock bands. These are hypothetical geometric units and *not* mappable rock units. Designated from A to I, these units outline the geometry of the dome. The number of units is arbitrary and another choice of units could have been made.

Following the procedures described above, 171 modal foliation orientations were obtained. The best estimate for the concentration parameter K of the whole area is 32, indicating large measurement errors and considerable roughness of the folded surfaces.

Six domains within which the folding is statistically cylindrical can be established (figure 4). The two transverse faults make two natural domain boundaries. The other domain boundaries were more difficult to position because of both the curved nature of the dome (and hence the gradual change in orientation of the fold axis) and a small concentration parameter K. The fold axis orientations calculated as eigenvectors, the associated normalized eigenvalues, and concentration parameters of the domains are presented in table 1. The normalized minimum eigenvalues show that domain 6 has the least degree of cylindricity, a result of conicity in parts of the dome. All domains were examined for conicity. Only domain 6 showed significant conical folding. The best fitting cone axis plunges 82° in the direction N229°E and the half apical cone angle of the cone described by the normals to the folded surface is 60°. The sum of the squares of the angles between the normals to the folded surface and the best fitting cone axis is 2325 (degrees squared). The standard deviation of the half apical cone angle is 12.6°. Consequently, the cone angle is 2.4 standard deviations away from 90°, which is a significant deviation from cylindricity. The goodness-of-fit test shows a good fit of the cone (χ^2 statistic is 4.1 with 3 degrees of freedom). It follows that the folding in domain 6 can be considered conical (figure 5).

Profiles (cross-section normal to the fold axis) and composite profiles were obtained. Composite profiles were obtained by rotation of domain segments instead of the whole domain because of the gradual change in fold axis orientation along the dome. The composite profile of domains 1 and 2 were obtained by the following sequential steps. First, the north segment of domain 1 was rotated towards the fold axis orientation of the south segment of domain 1. The two segments were then rotated together towards the fold axis orientation of the north segment of domain 2, and, finally, the three segments were rotated together towards the

Table 1. Fold axis orientations, eigenvalues and concentration parameters of the Tulip Lake area

	Fold axis						
Domain	Trend	Plunge	$\lambda3/n$*	n*	m*	r*	K*
1	8°	45°	0.0104	19	6	55	53.6
2	21°	8°	0.0230	19	5	40	27.1
3	199°	2°	0.0147	31	8	74	39.5
4	203°	9°	0.0149	48	18	135	38.5
5	203°	6°	0.0152	36	12	86	31
6	201°	37°	0.0449	18	6	39	20.4

*Note: $\lambda3$ - minimum eigenvalue
n - number of modal foliations
m- number of sub-areas with repeated measurements
r - number of repeated measurements
K- concentration parameter

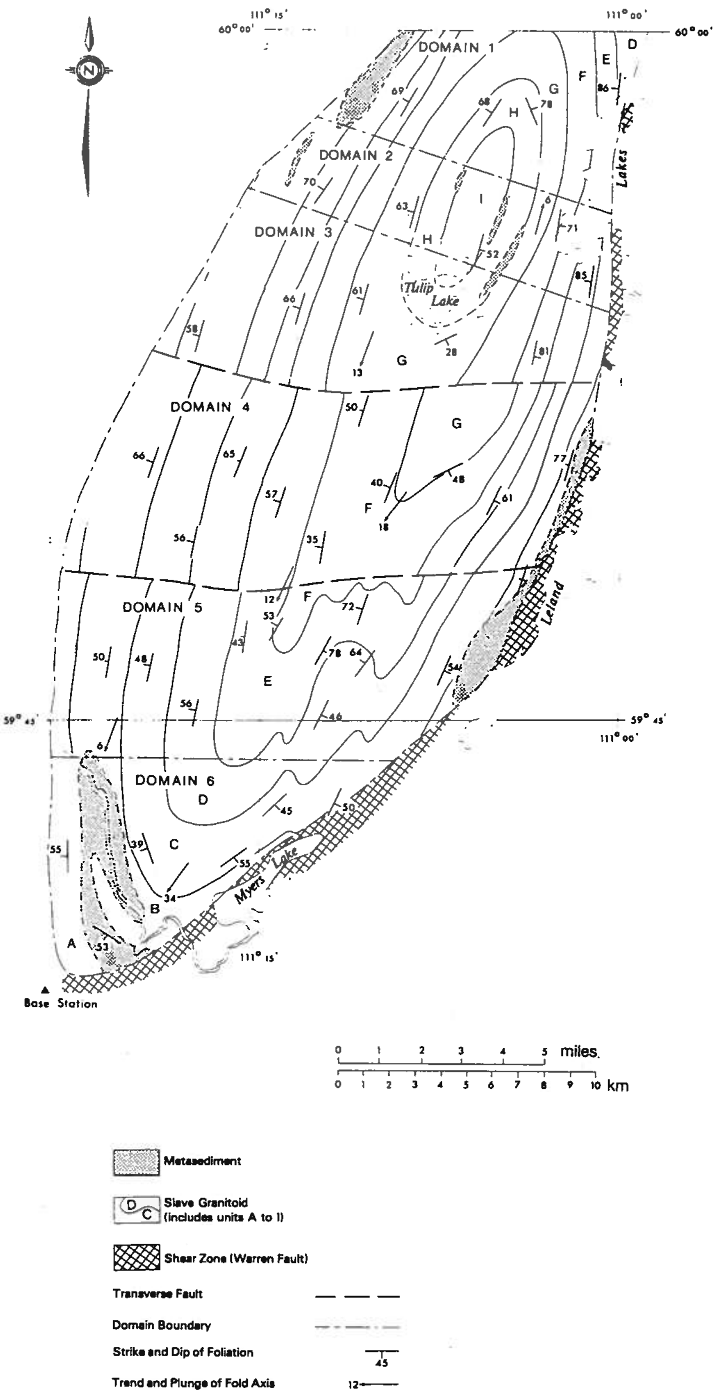

Figure 4. Geological map of of the Tulip Lake Dome (based on Godfrey and Langenberg, in prep. a and b). Units A through I of the Slave Granitoids are based on modal foliation orientations and the location of metasedimentary rock bands.

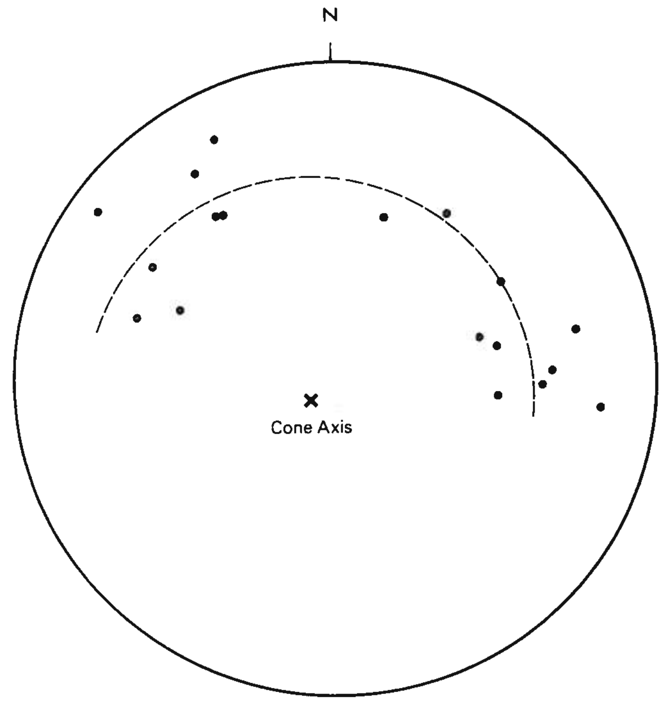

Figure 5. Lower hemisphere equal area projection of the poles to foliation in domain 6 of the Tulip Lake area. The best-fitting small circle (projection of a cone) is indicated by the dashed curve.

fold axis orientation of the south segment of domain 2. The composite profile was then obtained in the usual manner (figure 6). Some of the modal foliations do not fit form lines based on most of the foliations. In these cases, the foliations are oblique to the contacts between units. A composite profile for domains 5 and 6 was obtained in the same way (figure 6).

Figure 7 shows profiles of the two central domains that have gentle, south plunging fold axes, resulting in the projected data stations being clustered together.

Horizontal and vertical sections were used to construct block diagrams of the southern three domains (figure 8). This is a composite figure of three plots from three different observational positions, one for each block. For this reason, the blocks have slightly different scales. Elevations are assumed to be constant in northeastern Alberta and the down-plunge projections on the top faces of the blocks are identical to the map of figure 4.

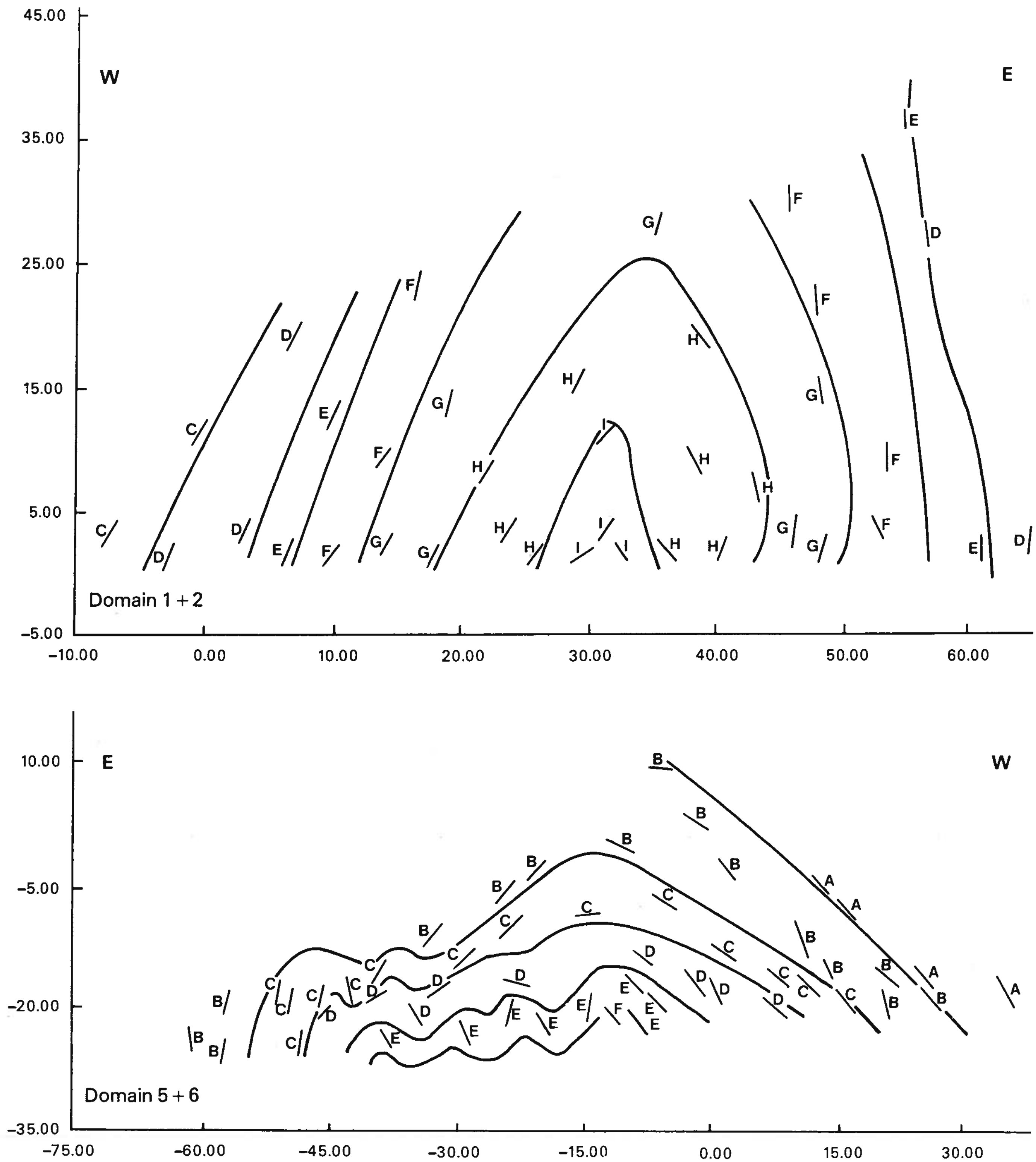

Figure 6. Composite structural profiles (sections perpendicular to the fold-axes) through the northern (top) and southern (bottom domains of the Tulip Lake area. The symbols used are shown on figure 4. The values along the axes are in tenths of a mile. This is an interpreted computer plot.

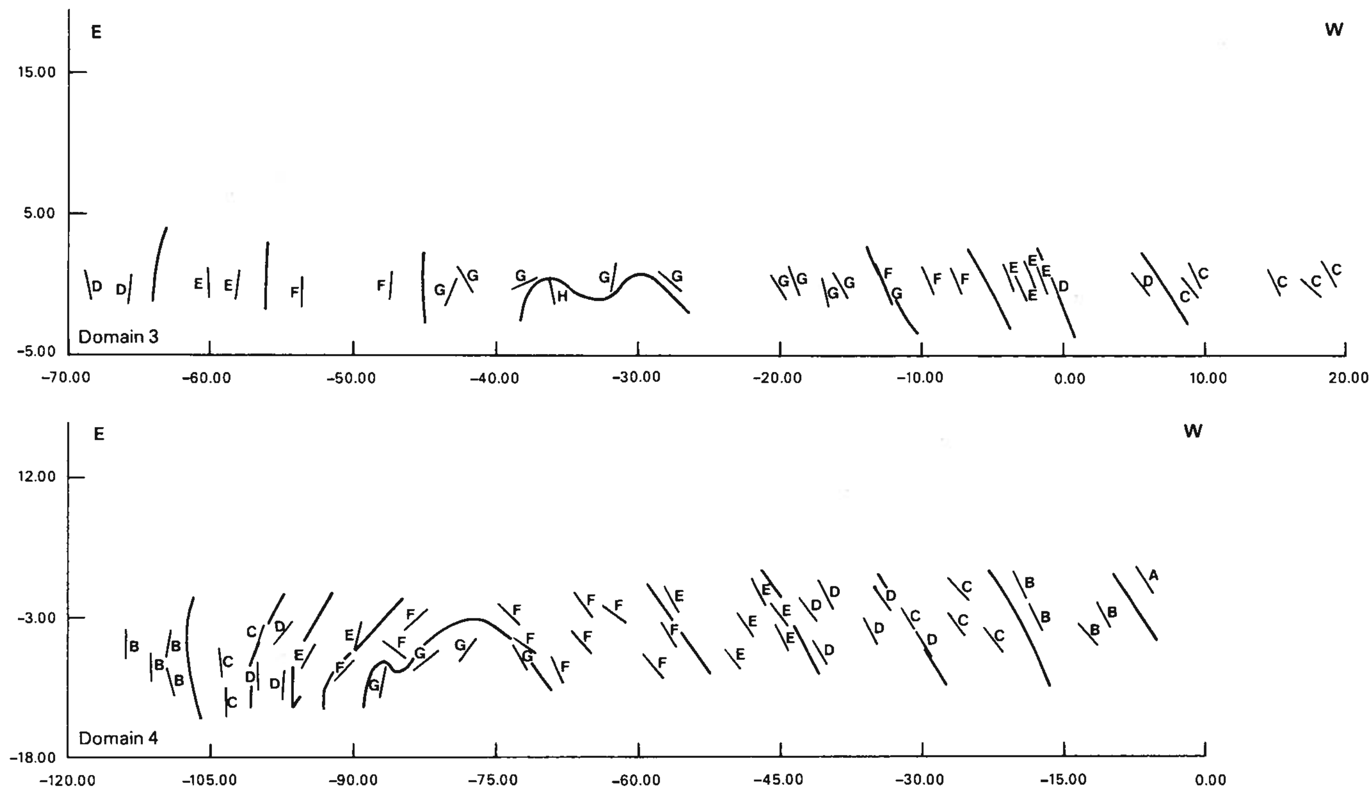

Figure 7. Structural profiles through domains 3 (top) and 4 (bottom) of the Tulip Lake area. The symbols used in this figure are the same as for figure 5. The values along the axes are in tenths of a mile. This is an interpreted computer plot.

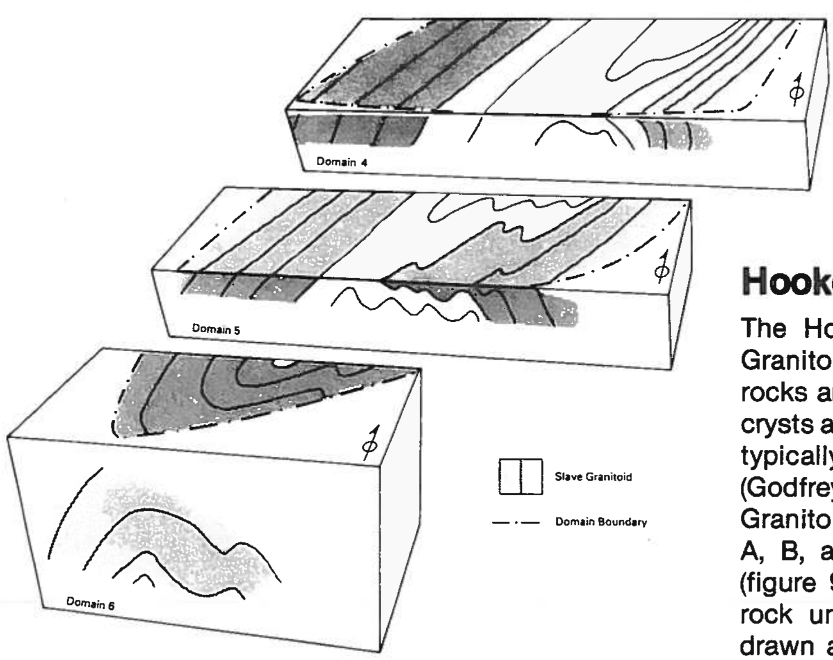

Figure 8. Perspective block diagrams of the southern three domains of the Tulip Lake area, based on the computer plots, viewed towards the north.

Hooker Lake area

The Hooker Lake area is underlain by Arch Lake Granitoids, which define a basin (figures 1 and 9). The rocks are characterized by potassium feldspar megacrysts aligned with the foliation. These megacrysts are typically flattened, giving the rock an augen-structure (Godfrey and Langenberg, in prep. a). The Arch Lake Granitoids of this area are arbitrarily divided into units A, B, and C on the basis of foliation orientations (figure 9). These geometric units are *not* mappable rock units. Their shapes are based on form lines drawn along the strikes of the modal foliations with the help of structural information from aerial photographs. The number of geometric units is arbitrary.

The foliation is represented by 120 modal foliation orientations and an overall concentration parameter K for the study area is estimated to be 26. Three cylindrical domains can now be established (figure 9). All three domains have north-plunging fold axes, with a gradual decrease in plunge towards the north. The fold axis orientations calculated as eigenvectors, the associated normalized eigenvalues, and concentration parameters of the three domains are presented in table 2.

The three domains were tested for conicity. Domain 2 has a cone axis plunging 70° in direction N31°E and a half apical cone angle of the cone described by the normals to the folded surface of 59.5°. The sum of squares of the angles between normals and the cone axis is 2387 (degrees squared) and the standard deviation of the cone angle is 11°. Consequently, the cone angle is 2.8 standard deviations away from 90°, which is significant. There is a good fit of the folded surface to an ideal cone (χ^2 statistic is 1.3 with 3 degrees of freedom). Thus, the folding in domain 2 can be considered conical (figure 10).

The folding in domain 1 is not significantly conical. However, if domains 1 and 2 are joined together, they show significant conical folding with a similar cone axis orientation and cone angle as in domain 2. The method of down-plunge projection (parallel to the best-fitting cylindrical fold axis) to construct cross-sections is still applicable in domain 2 because the domain is narrow in the direction of this fold axis.

Figure 11 presents the profiles of domains 1 and 2, and shows the open nature of the basin. Figure 12 gives the profile of domain 3 and it shows the continuation of the basin plus an antiform. The antiform is of particular interest. The crescent-shaped structure formed by this antiform (figure 9) represents a crescent-shaped diapir. Consequently, it forms a dome near the center of the basin.

Figure 13 contains block diagrams. The blocks are viewed towards the south and are drawn in perspective projection, based on the computer plots. Because the plot is a composite from three different observational positions, one for each block, the blocks have slightly different scales.

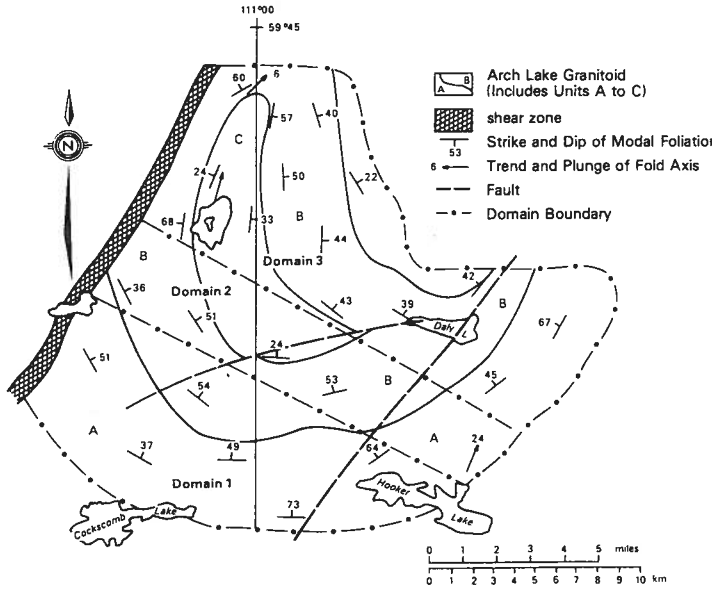

Figure 9. Geological map of the Hooker Lake area (based on Godfrey and Langenberg, in prep. a). Units A, B and C of the Arch Lake Granitoids are based on the modal foliation orientations.

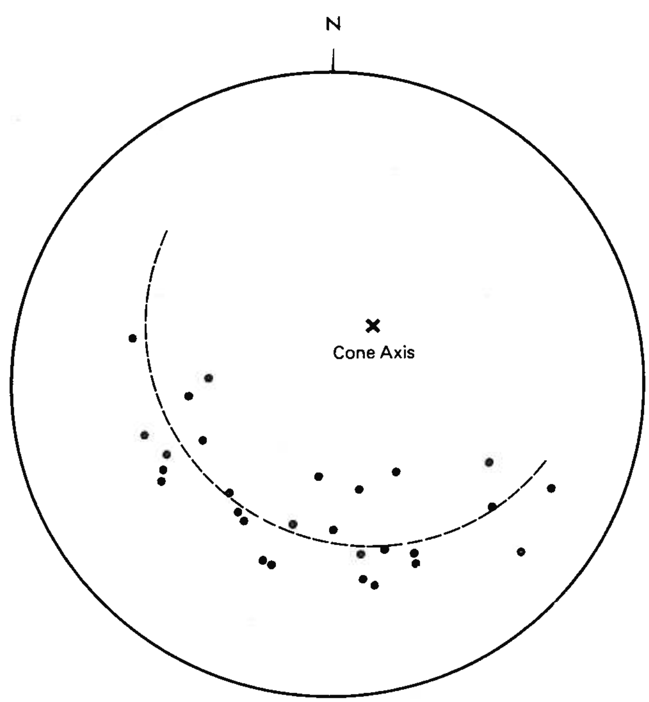

Figure 10. Lower hemisphere equal area projection of the poles to foliation in domain 2 of the Hooker Lake area. The best-fitting cone is indicated by the dashed curve.

Table 2. Fold axis orientations, eigenvalues and concentration parameters of the Hooker Lake area

Domain	Fold axis Trend	Fold axis Plunge	$\lambda3/n$*	n*	m*	r*	K*
1	45°	40°	0.0253	38	19	114	30.6
2	19°	35°	0.0343	28	10	73	22.9
3	18°	20°	0.0373	54	20	120	23.8

*Note: $\lambda3$ - minimum eigenvalue
n - number of modal foliations
m- number of sub-areas with repeated measurements
r - number of repeated measurements
K- concentration parameter

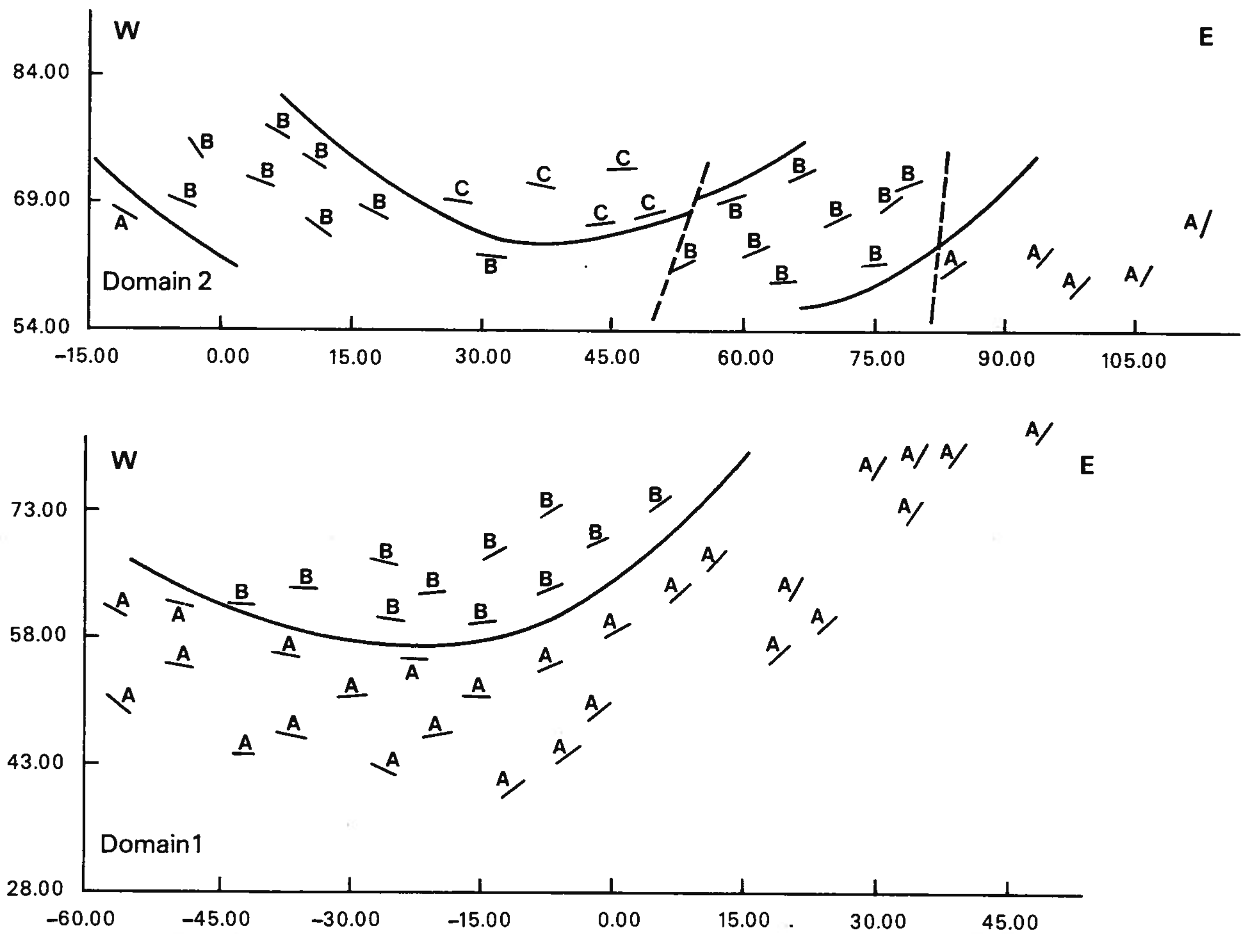

Figure 11. Structural profiles through domains 1 (bottom) and 2 (top) of the Hooker Lake area. The Arch Lake Granitoid units represented on these sections are shown in figure 10. The values along the axes are in tenths of a mile. This is an interpreted computer plot.

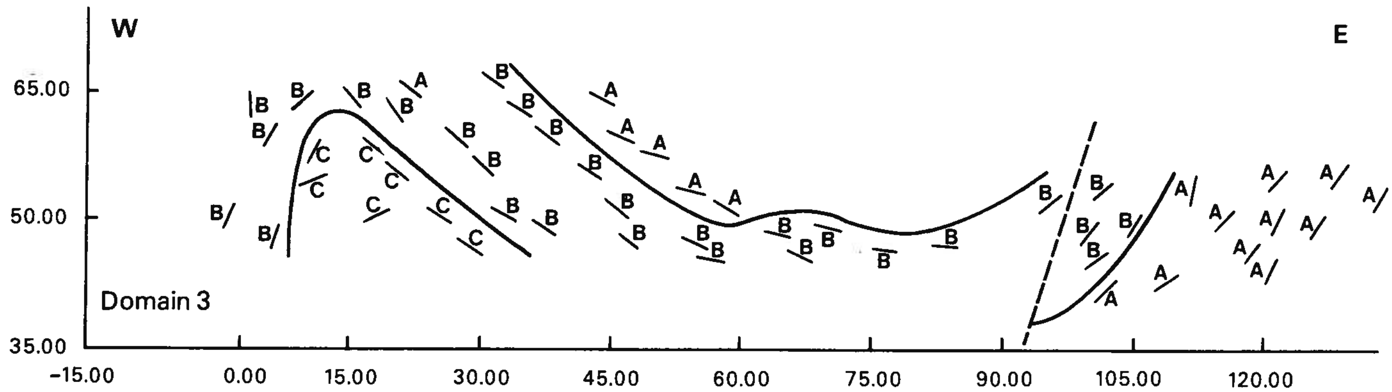

Figure 12. Structural profile through domain 3 of the Hooker Lake area. The symbols used are the same as for figure 11. The values along the axes are in tenths of a mile. This is an interpreted computer plot.

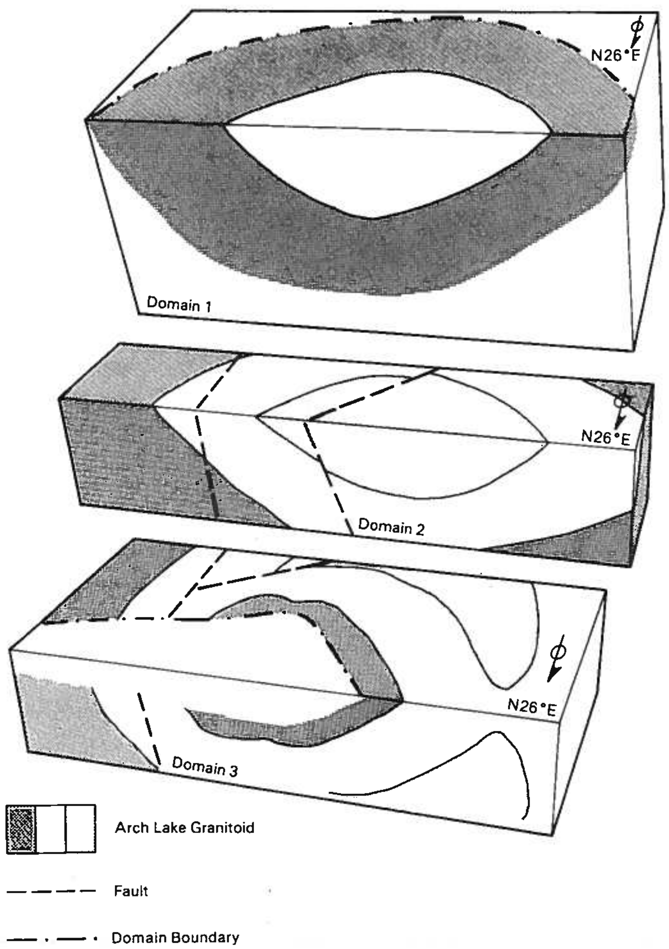

Figure 13. Perspective block diagrams of the three domains of the Hooker Lake area viewed towards the south, based on the computer plots.

Arch Lake area

The Arch Lake area includes the northern continuation of the Hooker Lake basin (figures 1 and 14). The area is largely underlain by Arch Lake Granitoids with minor Archean granite gneisses in the eastern part. These gneisses are peripheral to a domal structure in Arch Lake Granitoids south of Arch Lake (Godfrey and Langenberg, in prep. b).

The foliation can be represented by modal foliations and three statistical cylindrical domains have been established (see figure 14). The fold axis orientations calculated as eigenvectors and the associated normalized eigenvalues of the three domains are presented in table 3. The plunge of the fold axis steepens from 25° in domain 1 to 48° in domain 2. The boundary between these domains marks the termination of the Hooker Lake basin. Nowhere is the plunge of the fold axis southerly. This shows that the Hooker Lake basin is tipped towards the north. None of the domains show significant conical folding. The antiform in the western half of domain 1 is the continuation of the crescent-shaped dome of the Hooker Lake area. Figure 15 shows the profiles of domains 1 and 2.

Domain 3 defines an antiform with a north-plunging fold axis at the northern end of an elongated domal structure in Arch Lake Granitoids south of Arch Lake. The

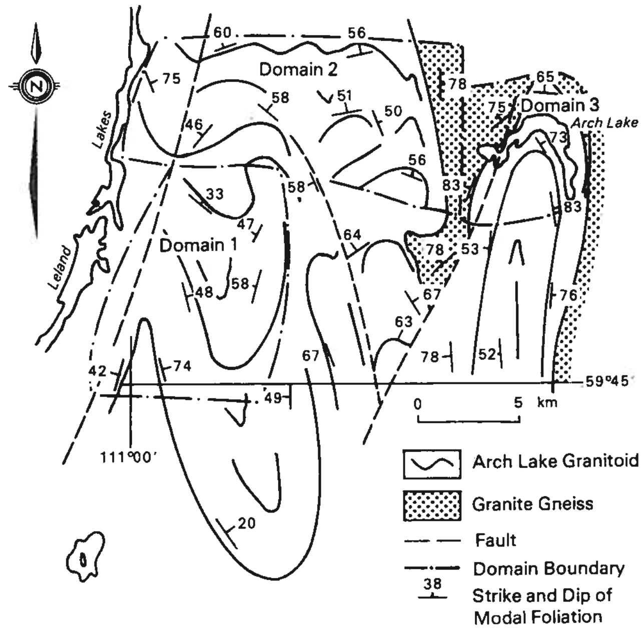

Figure 14. Geological map of the Arch Lake area (based on Godfrey and Langenberg, in prep. b).

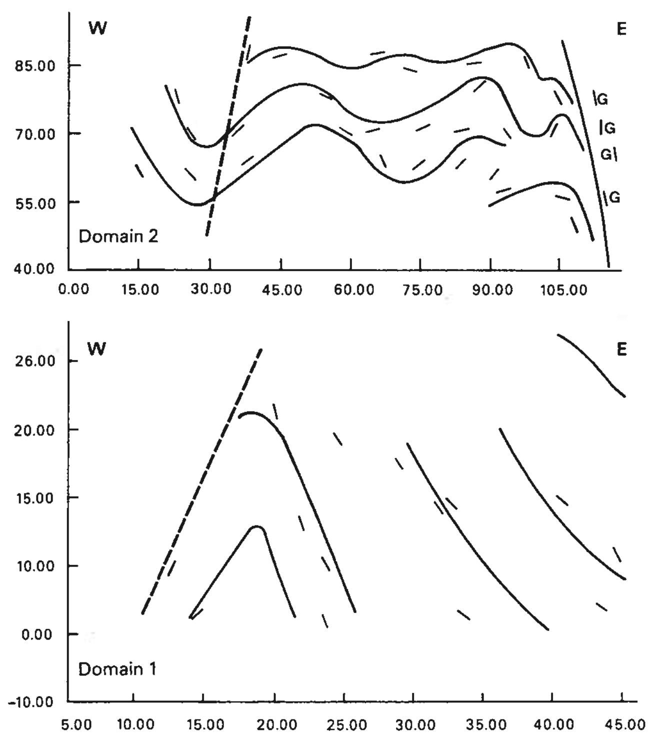

Figure 15. Structural profiles through domains 1 (bottom) and 2 (top) of the Arch Lake area—G indicates Granite Gneiss. The values along the axes are in tenths of a mile. This is an interpreted computer plot.

Table 3. Fold axis orientations and eigenvalues of the Arch Lake area

	Fold axis			
Domain	Trend	Plunge	$\lambda 3/n$	n
1	5°	25°	0.0422	20
2	359°	48°	0.0408	33
3	353°	65°	0.0219	11

shape of Arch Lake (and its name) reflect the antiform. The granite gneisses form a synformal keel between the dome of domain 3 and the mild domal structure of domain 2. A prominent transverse fault through the west arm of Arch Lake marks the termination of this synform to the south.

Disappointment Lake area

This area is underlain by foliated Slave Granitoids with mappable inclusions of quartzo-feldspathic rocks (designated as paragneisses on figure 16). These xenoliths are considered part of the parent material of the granitoids (Langenberg and Nielsen, 1982) and define ghost-stratigraphy. The area is bounded to the south by a prominent fault through Disappointment Lake (Godfrey, in prep.). Modal foliations were obtained and the concentration parameter K for the area is estimated to be 25. Consequently, the magnitude of the roughness of the folded surfaces and measurement errors are similar to those in the Tulip Lake and Hooker Lake areas. The several antiforms and synforms in this study area have been shown to be statistically cylindrical. The fold axis plunges 64° in the direction N343°E. The normalized minimum eigenvalue (minimum eigenvalue divided by number of data stations) is 0.0289 and the number of modal foliation orientations is 28. Figure 17 shows the cross-section perpendicular to the fold axis of the area. The plane of the profile only makes an angle of 26° with the topographic surface. Consequently, the outcrop pattern resembles the profile.

The selected study area can now be tied in with the surrounding region. Figure 18 shows that the area north of Disappointment Lake forms the core of a dome. The antiforms are second order domes (Schwerdtner *et al.*, 1979), of which the southern parts are faulted out. The main displacement along the fault takes place in the core of the dome. The Turtle Lake basin (centered on Turtle Lake) has Arch Lake Granitoids in its core. In the east the shear zone is largely in the Archean basement gneiss complex.

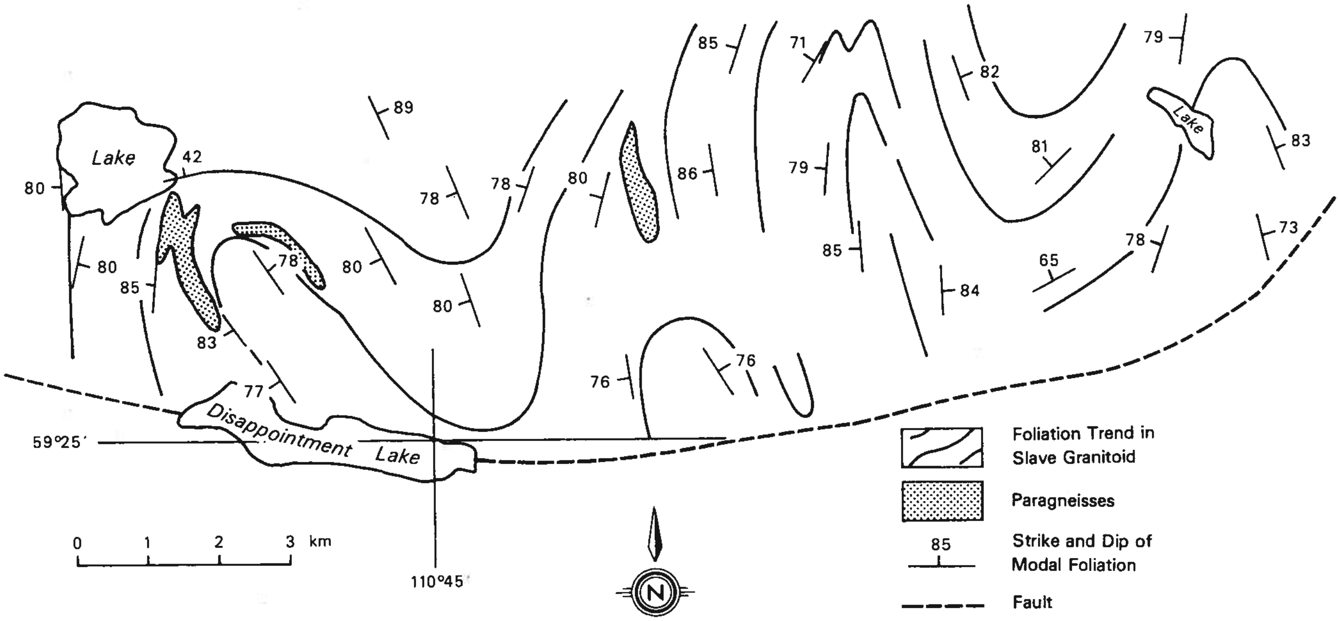

Figure 16. Geological map of the Disappointment Lake area (based on Godfrey, in prep.). The paragneisses include rocks mapped as granite gneisses as well as high-grade metasediments.

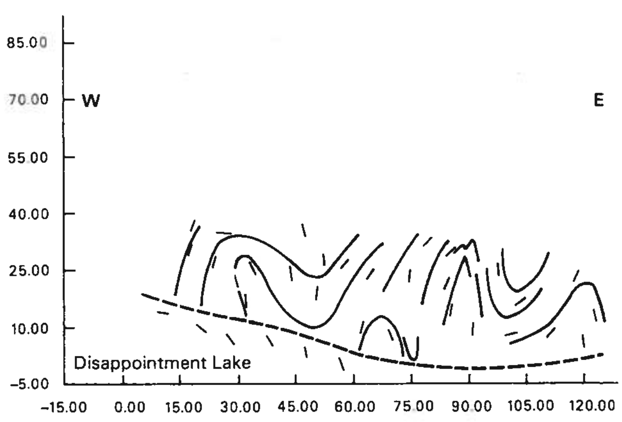

Figure 17. Structural profile of the Disappointment Lake area. The values along the axes are in tenths of a mile. This is an interpreted computer plot.

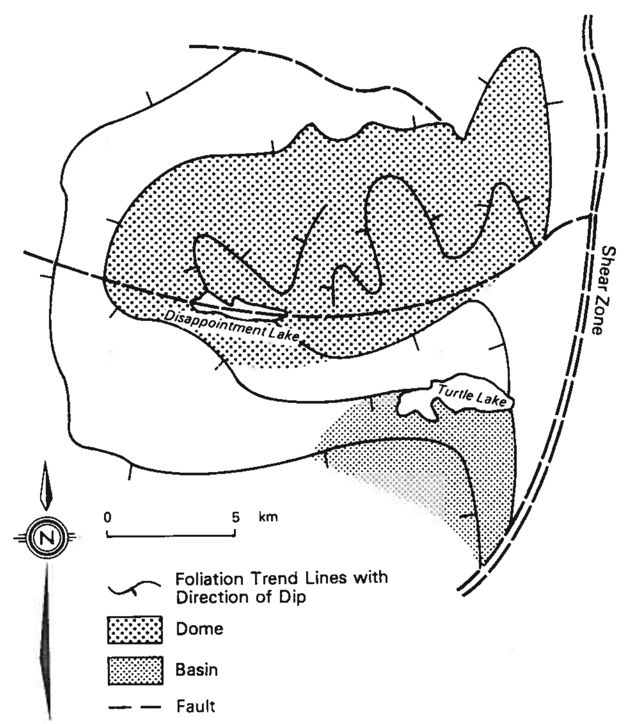

Figure 18. Structural interpretation of the area surrounding Disappointment Lake.

Wylie Lake area

The Wylie Lake area is largely underlain by foliated Wylie Lake Granitoids (Godfrey, 1980a), which can be grouped into two units, granodiorites and tonalites (figure 19). These granitoids have formed by ultrametamorphism from migmatitic granite gneisses, which crop out west and north of the granitoids. This process represents the remobilization of an Archean basement during the Hudsonian orogeny. Granite gneisses occupy the core of the dome centered at Wylie Lake.

Finer grained, banded, quartzo-feldspathic rocks are mapped as metasediments. The presence of almandine and hornblende attests that these rocks experienced amphibolite facies conditions at least. The occurrence of metasediments within the granitoids indicate that they may also form part of the parent material for the granitoids.

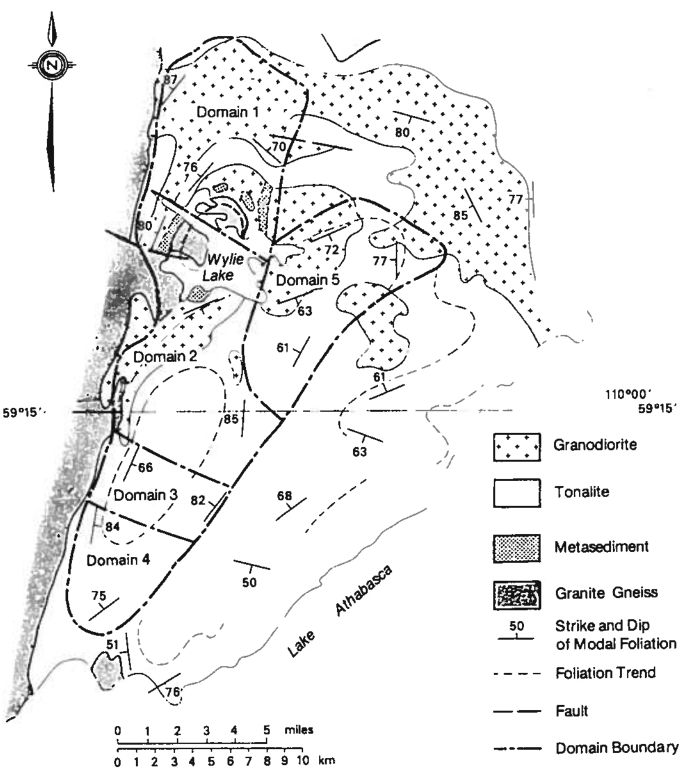

Figure 19. Geological map of the Wylie Lake area (based on Godfrey, 1980a).

Modal foliation orientations are obtained and an overall concentration parameter K for the area is estimated as 13. This is the lowest K value obtained, indicating the largest irregularities of folded surfaces in granitoids in the areas studied.

At least five cylindrical domains can be established (figure 19). Domain 1 covers the northern half of the dome; domain 2 the southern half of the dome plus part of a basin structure. Domains 3, 4, and 5 cover the remainder of the basin. East-west trending folds can be seen in the eastern part of the area, although they cannot be traced into the dome and basin.

The fold axis orientations calculated as eigenvectors, the associated normalized eigenvalues, and concentration parameters of the domains are presented in table 4. None of the domains shows significant conical folding. Figures 20 and 21 show the profiles of domain 1 and domain 2, respectively.

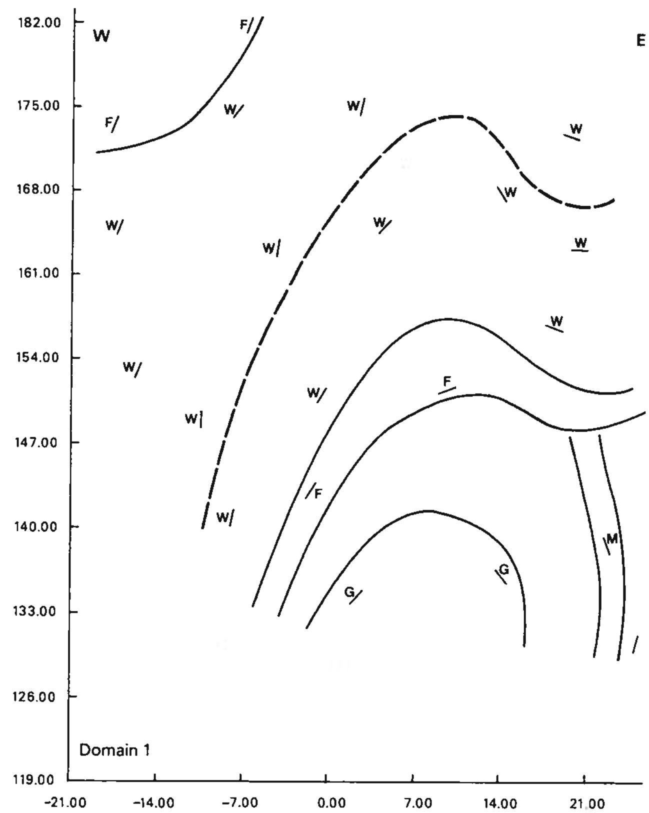

Figure 20. Structural profile through domain 1 of the Wylie Lake area. F is tonalite, W is granodiorite, M is metasediments, and G is granite gneiss. The values along the axes are in tenths of a mile. This is an interpreted computer plot.

Table 4. Fold axis orientations, eigenvalues and concentration parameters of the Wylie Lake area

Domain	Fold axis Trend	Fold axis Plunge	λ3/n*	n*	m*	r*	K*
1	14°	57°	0.0280	23	3	21	18.3
2	212°	55°	0.0294	31	13	128	12.3
3	29°	9°	0.0138	9	-	-	-
4	25°	48°	0.0132	10	2	21	13.7
5	230°	56°	0.0462	16	4	33	11.2

*Note: λ3 - minimum eigenvalue
n - number of modal foliations
m- number of sub-areas with repeated measurements
r - number of repeated measurements
K- concentration parameter

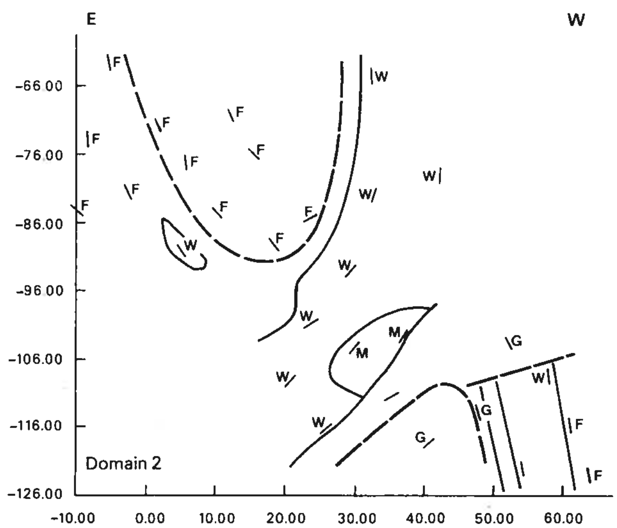

Figure 21. Structural profile through domain 2 of the Wylie Lake area. The symbols used are the same as for figure 20. The values along the axes are in tenths of a mile. This is an interpreted computer plot.

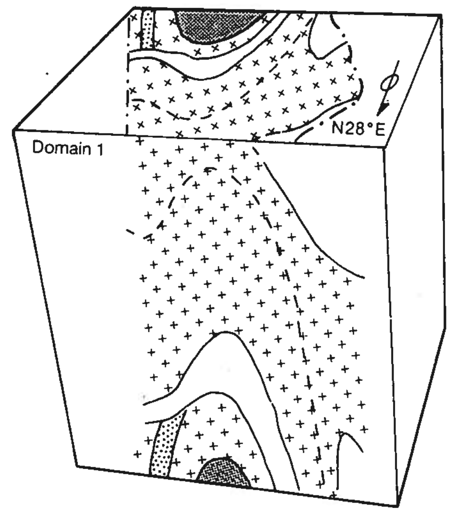

Figure 22. Perspective block diagram of domain 1 of the Wylie Lake area based on the computer plot and viewed towards the south. For legend see figure 19.

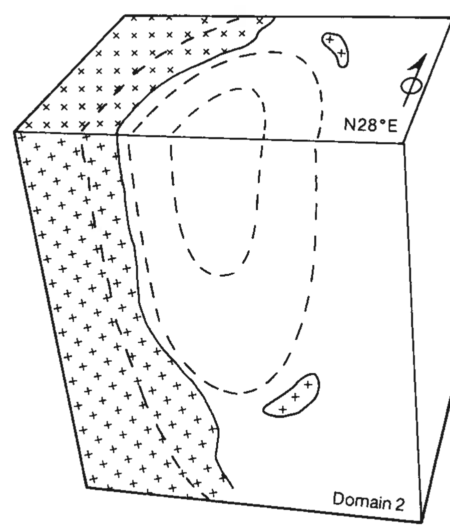

Figure 23. Perspective block diagram of the basin in domain 2 of the Wylie Lake area based on the computer plot and viewed towards the north. For legend see figure 19.

Figure 22 gives the block diagram in a perspective projection of domain 1, viewed towards the south. Figure 23 shows the block diagram of the basin in domain 2, viewed towards the north. The contacts between granodiorites and tonalites produce useful marker horizons in domain 1 and part of domain 2 only. In other areas, this contact tends to cut across the foliation trends.

St. Agnes Lake area

The St. Agnes Lake area is underlain by migmatitic granite gneisses and metasediments of the Archean basement gneiss complex (Godfrey and Peikert, 1963; Godfrey, 1966). Some Aphebian granitoid bodies are found north of St. Agnes Lake (figure 24). The most useful lithological contacts are those between the high-grade metasediments and the granite gneisses. These contacts, plus the shape of St. Agnes Lake, define a major antiformal structure.

The geometry of structures in the Archean gneisses is more complex than that of the Aphebian granitoids. The Archean granite gneisses and metasediments show tight to isoclinal folding of the foliation on a mesoscopic scale. In places, Aphebian granitoid material transects these folds. Consequently, these folds are older than the granitoids, which were formed by anatexis of the parent Archean granite gneisses and metasediments. During formation and emplacement of the granitoids, the gneisses are deformed for the second time. Therefore, greater complexity of structures are found in the gneisses. For this reason, a half-mile (0.8 km) grid was used to subdivide the St. Agnes Lake area into smaller subareas for data reduction. A four-times finer grid is generated in this area compared to other selected study areas.

Modal foliations are obtained for all subareas in the usual manner. The precision parameter K is estimated to be 9. This low precision parameter value reflects the structural complexity described above and the presence of mesoscopic folding. Mesoscopic folding is absent in the Aphebian granitoids.

Folding in the areas around St. Agnes Lake and around Spider Lake is shown to be statistically cylindrical. Consequently, the areas form domains (figure 24). The area around Spider Lake shows tight to isoclinal folding as indicated by the foliation trends and the normalized eigenvalues (which are 0.8175, 0.1612 and 0.0213). Thus, the girdle distribution of the normals to the foliation-planes approaches a single cluster maximum. The fold axis is plunging 59° in the direction N30°E. The profile of this domain is shown in figure 25.

Tight-to-isoclinal folding is representative of much of the basement gneiss complex. In the area around St. Agnes Lake, however, a different type of folding is

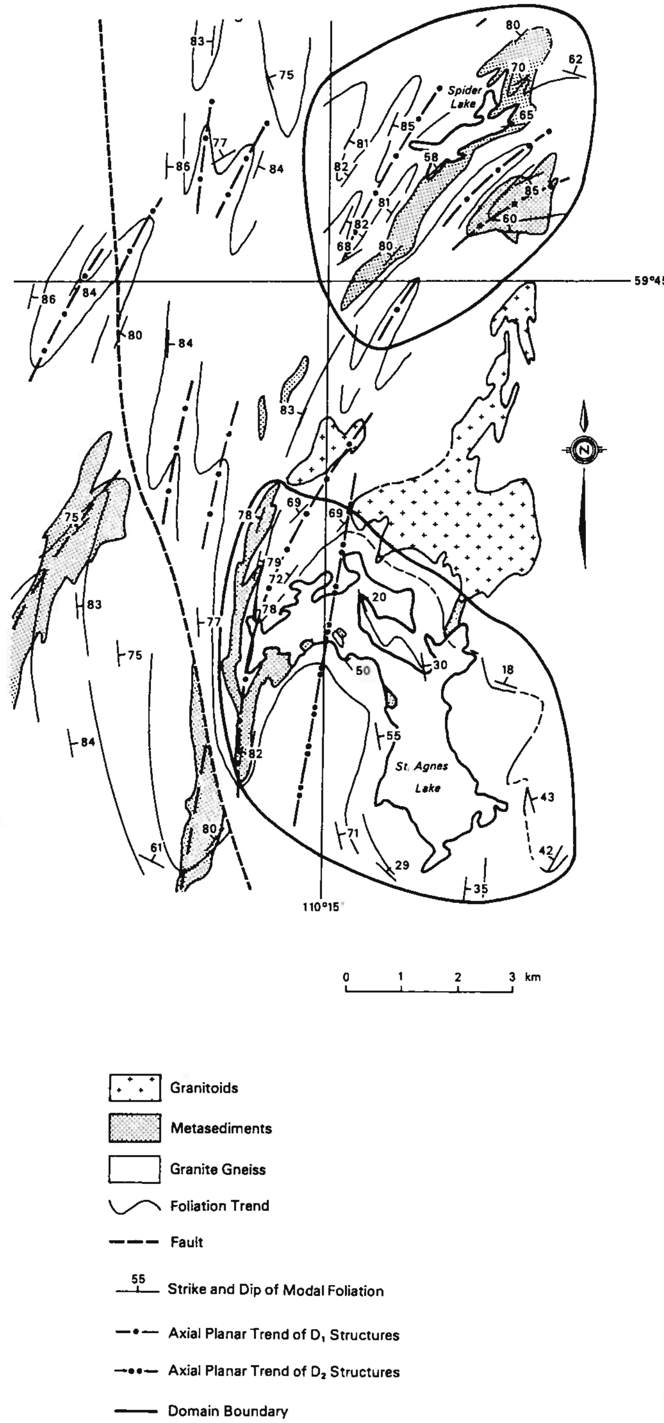

Figure 24. Geological map of the St. Agnes Lake area (based on Godfrey and Peikert, 1963, and Godfrey, 1966).

encountered. The major structure in this domain is an antiform, defined by foliation measurements and a curved band of metasediments. The fold axis in this domain plunges 30° in the direction N26°E. The profile of the domain given in figure 26 shows the open nature of the antiform. This cross-section and the map in figure 24 show a tight fold just northwest of St. Agnes Lake to be affected by the open antiform. This tight fold can be traced along the strike to the tight-to-isoclinal folds of the Spider Lake area. These macroscopic folds are correlated with the tight-to-isoclinal mesoscopic folds of the Archean basement gneiss complex. In places, these mesoscopic folds are transected by Aphebian granitoids. The mesoscopic folds are, therefore, older than the Aphebian granitoids and are most probably of Archean age. This early phase of deformation is called D_1. The domes and basins in the Aphebian granitoids are younger and are called D_2 structures. The open antiform defined by St. Agnes Lake is also younger than the tight D_1 folds and is correlated with a second phase of deformation (D_2).

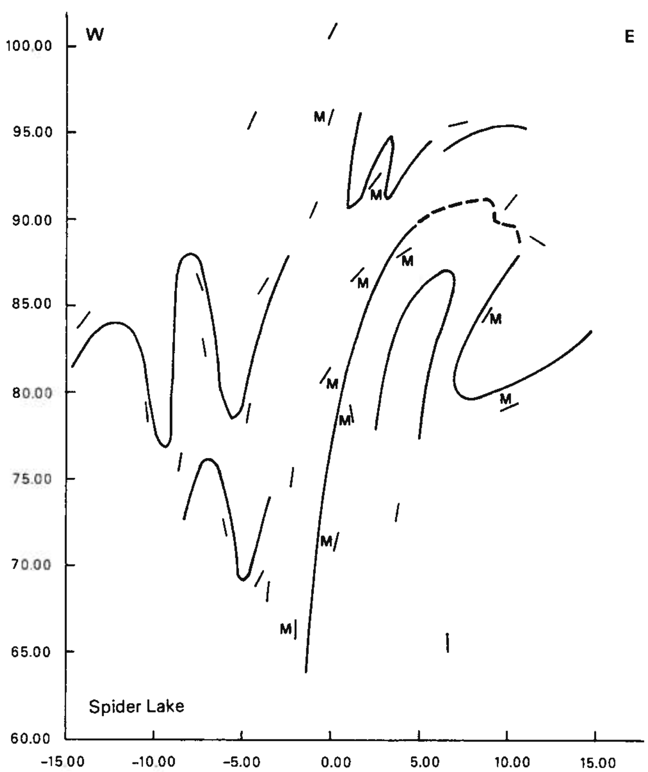

Figure 25. Structural profile through the Spider Lake domain of the St. Agnes Lake area — M indicates metasediments. The values along the axis are in tenths of a mile. This is on interpreted computer plot.

This antiform is related to a mild domal structure in granite gneisses southwest of St. Agnes Lake in the Alexander Lake area (Godfrey, 1980a). Tight D_1 folds in this area are deformed by the dome as shown by their gradual change of trend on figure 27 (see also figure 1).

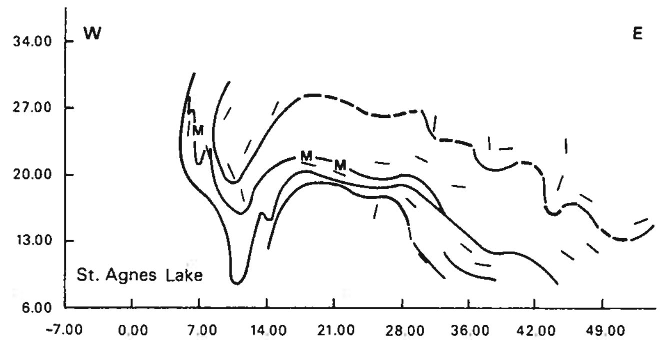

Figure 26. Structural profile through the domain centered on St. Agnes Lake — M indicates metasediments. The values along the axes are in tenths of a mile. This is an interpreted computer plot.

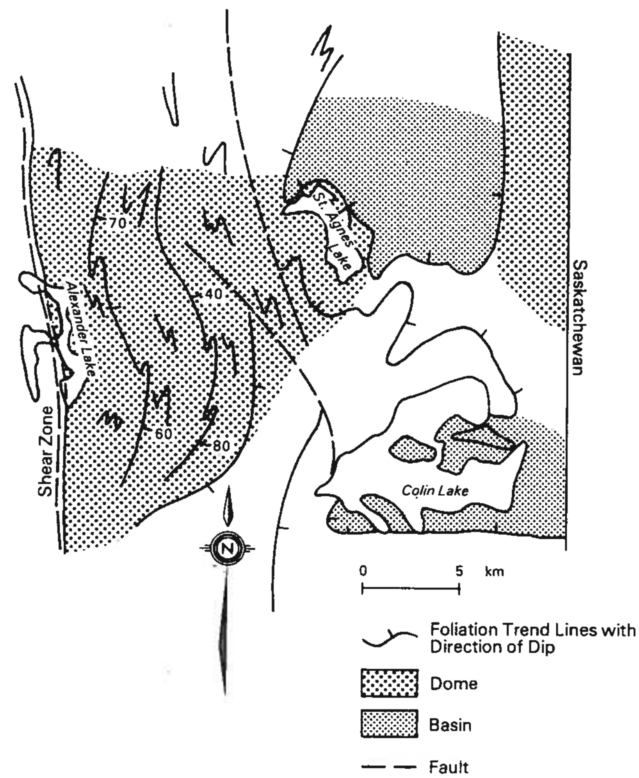

Figure 27. Structural interpretation of the Alexander Lake area.

Dome and basin geometry

The numerical methods are powerful tools in reproducing the geometry of macroscopic structures in Precambrian terrains. The information obtained in the study areas is used to select measurements from the published and unpublished 1:31 680 scale district maps for transferal to a 1:250 000 base map. The model of domes and basins obtained from the study areas is used in the selection of measurements for transferals in the remaining areas. The result of this compilation is the regional structural geology map (figure 1). The macroscopic structures emerging from this plot are largely domes and basins transected by straight shear zones and faults.

The information presented on figure 1 can now be summarized as shown in figure 28. Reference to figure 2 shows the lithologies of the major structures illustrated in figure 28. The Archean basement gneiss complex forms a synformal keel between Aphebian granitoids. A mild domal structure occurs in this keel in the St. Agnes Lake area. The main shear zone through Charles Lake, called the Allan Fault (Godfrey, 1958a), is largely confined to the Archean granite gneisses.

The Colin Lake Granitoids show a domal structure, that is probably largely situated in Saskatchewan, and a basin centered on Colin Lake. The Wylie Lake Granitoids reveal a basin surrounded by domes.

West of the basement gneiss complex the Slave Granitoids are characterized by domes. The sections dealing with the Tulip Lake and Disappointment Lake areas describe the most prominent ones. Other domes occur northwest and south of Ryan Lake. A basin north of Ryan Lake is truncated by a major fault.

The Arch Lake Granitoids contain basins in the Hooker Lake area and southwest of Turtle Lake. Another basin is seen in the Arch Lake Granitoid body along La Butte Creek. This basin is situated between two domes. The eastern boundary of the main Arch Lake Granitoid body has an elongated dome south of Arch Lake.

The La Butte Granitoids north of La Butte Creek (shown on figure 2 as 'Other Granitoids') are found in a domal structure. The Chipewyan Granitoids near Ft. Chipewyan (also shown as 'Other Granitoids') reveal a basin between two domes, indicating a general domal structure.

Elongated domes in the granitoids do not show a preferred orientation or a systematic pattern. Elongations can be in a N-S, E-W, or NE-SW direction. The model of diapiric doming is preferred over a fold interference model because of this lack of preferred orientation and because of intrusive relationships between Archean gneisses and Aphebian granitoids.

The cross-sections of the domes can be conveniently compared with sections through diapiric models obtained using centrifuge systems. Sections of the domes in the Slave Granitoids discussed here correspond best to early stages of progressive deformation in Dixon's (1975, figures 10 and 11) cylindrical ridge models. The Tulip Lake dome can be described as an immature diapir. The other domes in the Slave Granitoids are probably immature diapirs as well. Only the dome in the Wylie Lake area may represent a more advanced stage of diapirism.

Doming is the end result of Archean basement reactivation as a consequence of large-scale heating. The heating also led to anatexis and generation of S-type granitoid bodies (Slave, Arch Lake, Wylie Lake, Colin Lake and La Butte Granitoids). These granitoids were emplaced at higher crustal levels by the process of diapiric doming. Anatexis is correlated with the Rb-Sr isochron of about 1900 Ma for the S-type granitoids. Doming of the granitoids is correlated with the domal D_2 structures in the Archean gneisses. Peak P-T conditions during anatexis were determined from coexisting metamorphic minerals to be $P = 5 \pm 0.7$ kbar and $T = 740 \pm 30\,°C$ (Langenberg and Nielsen, 1982). These conditions are within the moderate-pressure granulite facies field.

The higher metamorphic grade during metamorphic phase $M_{2.1}$ in the Tulip Lake area suggests that it was originally at a deeper crustal level (Langenberg and Nielsen, 1982). This concept is further supported by the abundance of supracrustal gneisses and metasediments east of the Allan Fault (which passes through Charles Lake) with only minor occurrences west of the fault. It may also indicate that doming continued longer in the immediate Tulip Lake area.

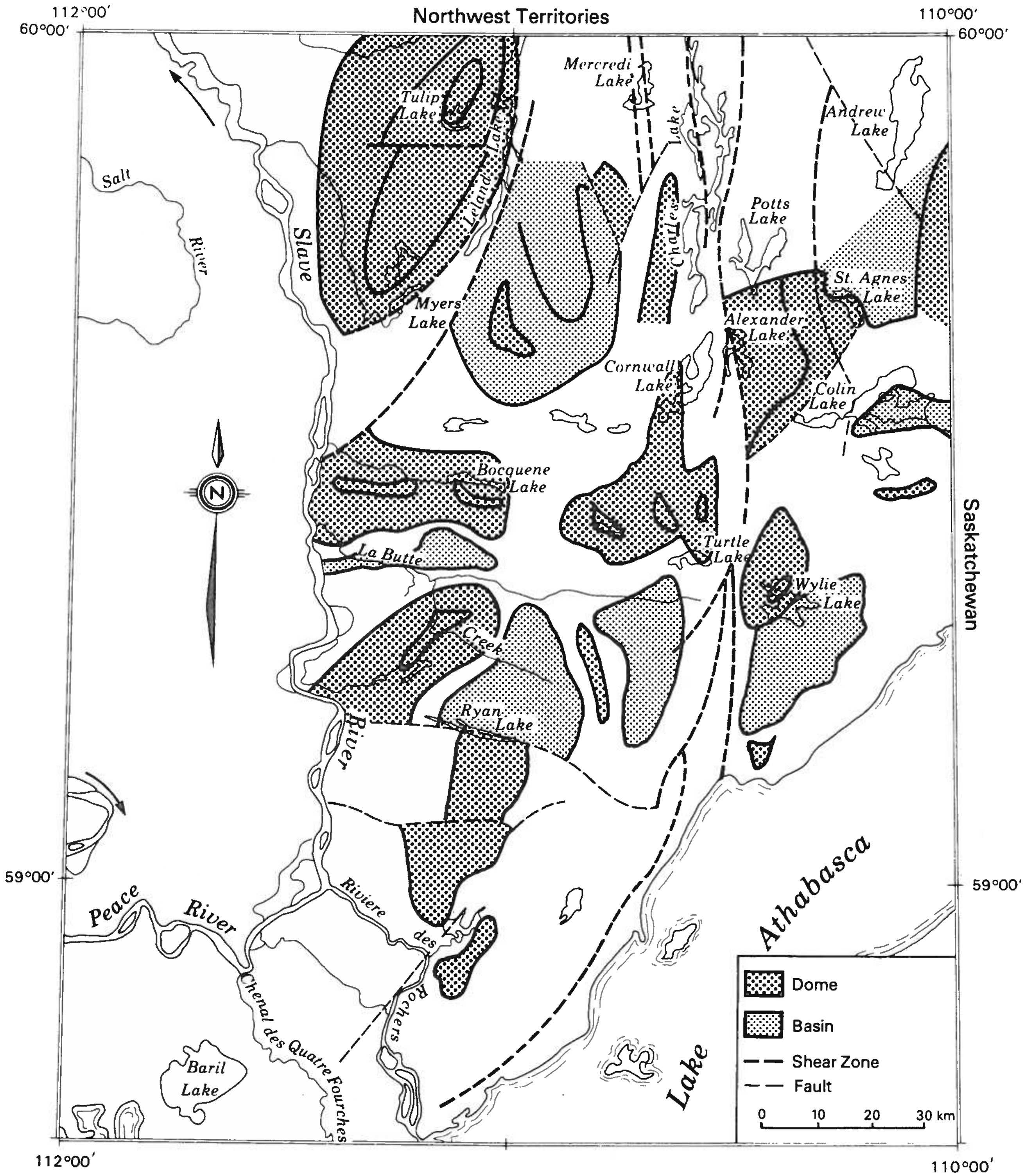

Figure 28. Simplified structural geological map of the exposed Canadian Shield of northeastern Alberta.

Metamorphic data is insufficient to allow comparison of doming in the Tulip Lake and Wylie Lake areas.

The large-scale regional heating resulted from high heat flow in the mantle some 500 km inland from a major subduction zone, the remnant of which are now in Saskatchewan (Nielsen *et al.,* 1981; Ray and Wanless, 1980). The deformational and metamorphic events can now be placed in a temporal framework (figure 29).

Faulting along large-scale shearzones is younger than the D_2 structures, because the shear zones transect or truncate the domes and basins. The shear zones are characterized by mylonites and greenschist facies minerals (Langenberg and Nielsen, 1982). K-Ar dating of these minerals shows that the mylonites formed 1790 ± 40 Ma ago. Some of the faults may have originated about the same time, as indicated by parallelism with the shear zones. Other faults cut the shear zones and, therefore, are younger.

Folding in the low-grade metasediments is probably related to the large-scale shear zones, indicated by the pro-grade greenschist mineralogy of the metasediments. Numerous faults indicate still younger, high-level, brittle deformation. Some northeast trending faults may be related to the formation of northeast trending sedimentary basins, south of the present study area. These basins formed in mid-Helikian time and were filled with the sediments of the Athabasca Formation (Ramaekers, 1980).

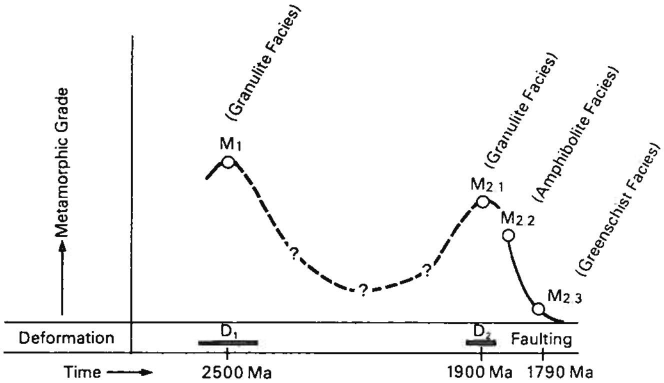

Figure 29. Temperoral framework of deformation and related metamorphism. Phases D_1, D_2 and large-scale faulting are fixed by isotope dating. Metamorphism is based on Langenbergy & Nielsen (1982).

Joints

Joints are fractures in rocks along which no appreciable movement has occurred. Joints in northeastern Alberta do not show evidence of slippage and are interpreted as extensional joints. In such a case, orthogonal joint systems can be expected (Price, 1966). Only major joint directions were measured in outcrop and they may be associated with a prominent escarpment.

Systematic joints occur with a spacing ranging from a few centimetres to five metres. A detailed study of fractures in a potential building stone site shows that systematic joints show well-defined, preferred orientations (Godfrey, 1979). This study confirms that the joints of the area are adequately represented by simply measuring the major joint directions in each outcrop.

Preferred orientations

The vertical and near vertical joint measurements are grouped by township. Townships where only a few measurements are available are grouped with neighboring townships. The technique of displaying joint data in smoothed rose diagrams is explained in the Structural Analysis section. Figure 30 (in pocket) shows rose diagrams of the joint orientations for the individual townships. This figure contains a total of 2122 major joint directions. The rose diagrams are placed in the center of the corresponding townships. In cases where measurements from adjacent townships were grouped, the rose diagram is placed on the mutual boundary of these townships.

Some preferred orientations show up clearly in these diagrams. Most townships show one prominent preferred orientation, together with one (sometimes two or three) other orientation. In several areas, these two preferred orientations are orthogonal. One such case is along the Slave River near Fort Fitzgerald and south of Wylie Lake. In these two latter cases, the joints can be attributed to a single orthogonal system. In other cases, where several preferred orientations are present, the angles between the joint sets vary and more than one orthogonal joint system may be present.

In order to obtain the regional joint systems of the whole area, joint measurements in eight specific areas are grouped together. These areas were chosen on the basis of reasonably consistent preferred orientations within groups of contiguous townships. These areas, which form homogeneous domains as far as jointing is concerned, are: Fort Fitzgerald, Tulip Lake, Myers Lake, Arch Lake, Hooker Lake, southern Wylie Lake, La Butte Creek and Fort Chipewyan. The smoothed rose diagrams (concentration parameter k for the von Mises smoothing function is again 50) of these domains are shown in figure 31.

From these diagrams, one or two preferred joint orientations can be identified. The orientations chosen are the peaks of the smoothed curves of figure 31, which are shown in figure 32. The readings fall into four groups. Group 1 has 2 strike readings in a narrow range from N52° to N53°E. Group 2 has 3 readings in the range from N75° to N90°E. Group 3 has 3 readings in the range from N125° to N145°E. Group 4 is the most poorly defined of the groups with 6 readings from N160° to N195°. The boundary between groups 3 and 4 is also poorly defined. These directions represent the regional jointing in the Shield of northeastern Alberta.

In outcrop, these joints are observed as orthogonal systems. No evidence of shear is observed and the joints are interpreted as extension joints. Therefore, the four groups of preferred orientations are considered to represent two orthogonal systems of extension joints.

System I comprises a joint set striking from N75° to N90°E and another set from N160° to N195°E. These are a roughly orthogonal system with N-S and E-W striking sets. This system is best represented in the southern Wylie Lake, La Butte, and Hooker Lake areas. It is slightly rotated in the Arch Lake area. A mixture of the two systems exists in the Tulip Lake and Myers Lake areas. System I is the most prominent joint system of the Precambrian Shield region.

System II consists of a set striking N52° to N53°E and another set striking N125° to N145°E. This system is best represented in the Fort Fitzgerald and Fort Chipewyan areas. It is also present, together with other systems, in the Tulip Lake and Myers Lake areas.

The potential building stone site in the Chipewyan Granitoid (Godfrey, 1979) just to the north of Fort Chipewyan predominantly shows System I. A minor amount of jointing conforming to System II is, however, present (Godfrey, 1979, figure 5). System II apparently becomes better developed towards the southern part of the Fort Chipewyan area. The rose diagram of the township block than encloses the building stone site shows a mixture of the two joint systems (Tp 113, R 8 on figure 30).

System II is parallel to the branch of the Allan Fault in the Fort Chipewyan area which, in turn, is approximately parallel to the north shore of Lake Athabasca. In the Fort Fitzgerald area, System II is subparallel to the southern branch of the Warren Fault (passing through Myers Lake) and also to the MacDonald Fault (through the East Arm of Great Slave Lake in the Northwest Territories).

Regional jointing and related stress fields

Joints are the youngest structural features of the area and can be observed to cut all other structural elements including foliations, shear zones, folds and faults. One joint set in outcrop tends to parallel nearby faults. Another set typically makes a small angle with the foliation, although the joints invariably dip more steeply than the foliation (except for occasional horizontal joints). All joints are assumed to be younger than other Precambrian Shield structural elements. A more difficult problem is determining exactly how old they are.

The regional joint systems of northeastern Alberta can be compared with the regional joint systems of nearby areas. Uranium City in northwestern Saskatchewan is the closest area where detailed information on jointing is available. Tremblay (1972, figure 15) shows conventional 10° rose diagrams of the area. The main joint directions are N5°E, N25°E, N50°E, N80°E, N115°E, and N140°E (figure 33). He concludes that these six directions represent three systems of extension joints and considers them to be of Precambrian age and contemporaneous with extensive faulting. Similarities to directions of jointing in northeastern Alberta are evident.

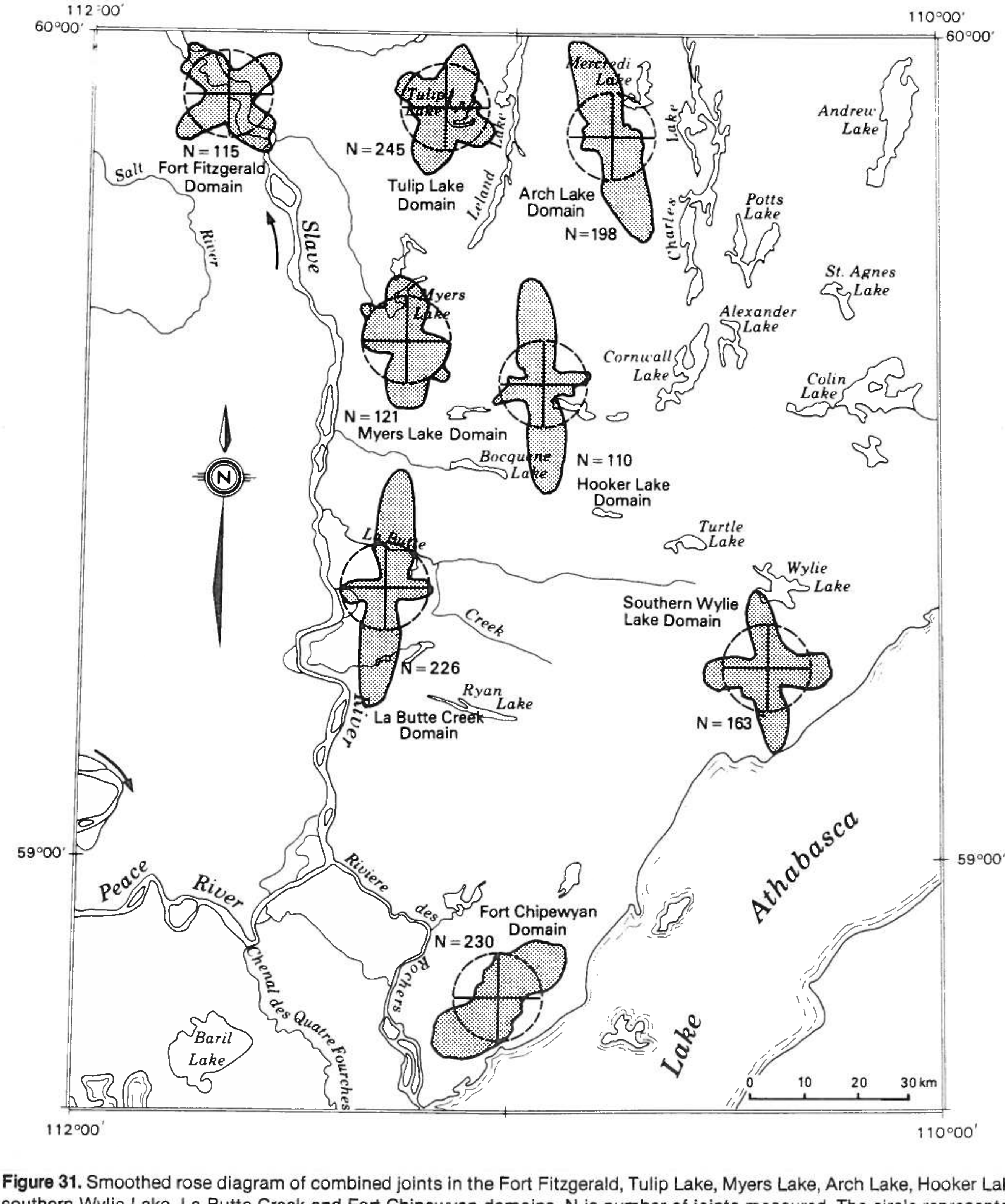

Figure 31. Smoothed rose diagram of combined joints in the Fort Fitzgerald, Tulip Lake, Myers Lake, Arch Lake, Hooker Lake, southern Wylie Lake, La Butte Creek and Fort Chipewyan domains. N is number of joints measured. The circle represents a uniform distribution.

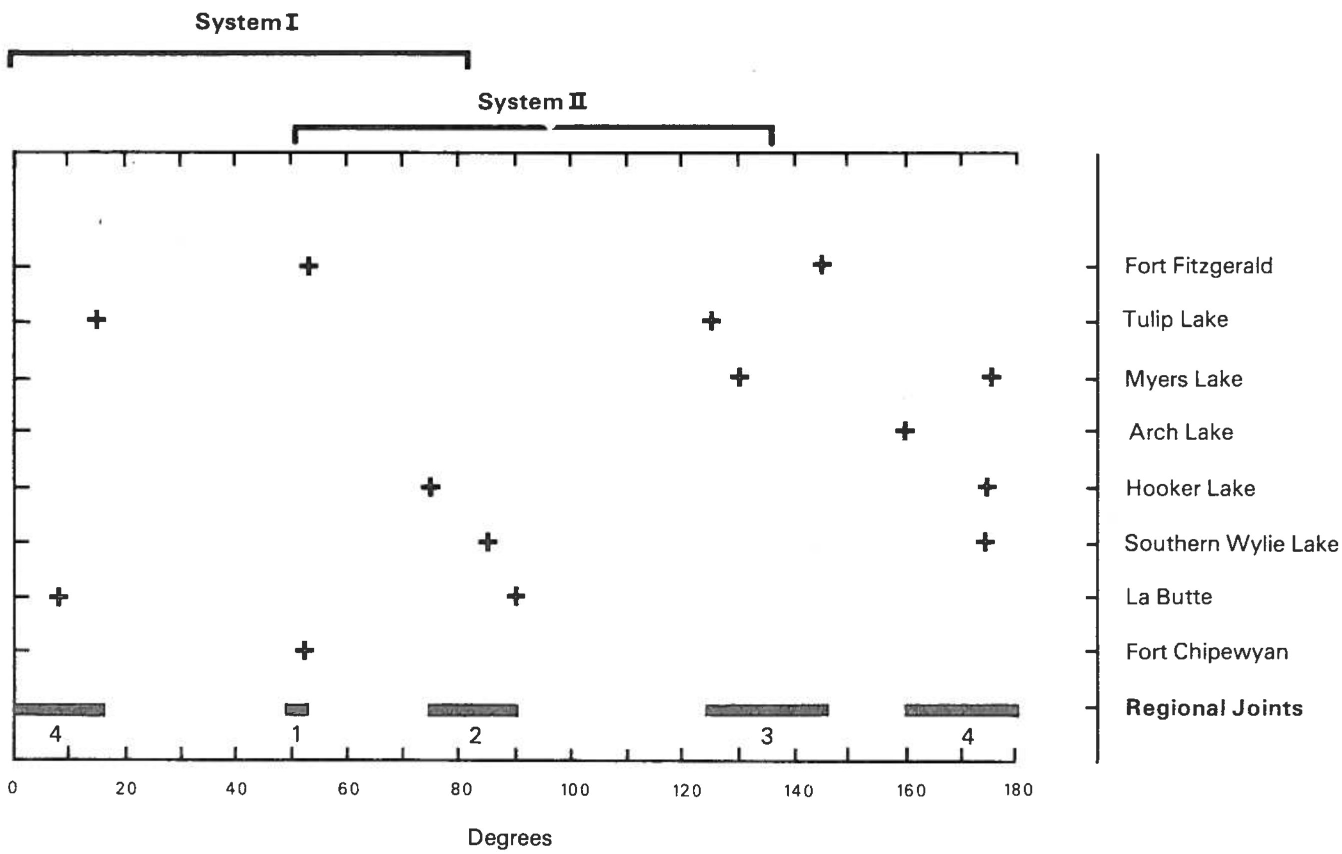

Figure 32. Summary of joint orientations observed in eight domains in northeastern Alberta.

Morton and Sassano (1972, figure 7) present data on jointing in the Fay Mine, Eldorado Nuclear Ltd., in the Uranium City area. They show vertical joints with strikes in the directions N65° to N75°E, N115°E, and N140° to N150°E (see figure 33). In addition to these vertical joints, they observe joints parallel and perpendicular to the St. Louis Fault (figure 34). This major fault strikes N70°E and dips 50°SE. They conclude that the vertical joints formed in the same stress field as that responsible for folding in the area. The other joints are assumed to have formed in the St. Louis Fault stress field. All joints are considered to be Precambrian in age by these authors. Similarities between joint directions in northeastern Alberta can be observed with the vertical joints of the Fay Mine, although N and E striking joints are lacking in the latter area.

For additional information on joints in the broad general region, one can turn to the nearby Phanerozoic rocks of the sedimentary basin of western Canada. Babcock (1975) studied jointing in the Fort McMurray area where the Devonian Waterways Formation and Cretaceous McMurray Formation show two regional orthogonal joint systems. One system is made up of sets that strike roughly N-S and E-W. The other system strikes approximately parallel and normal to the trend of the Cordilleran orogen to the west (about N50°E and N145°E, see figure 33). The strike directions of these regional joint sets extend throughout central and southern Alberta (Babcock, 1973, 1974). The photo lineaments in the Fort McMurray area trend parallel to N-S and NW-SE joints (Babcock and Sheldon, 1979). A NW-SE and NE-SW orthogonal lineament system is also found in the western Canadian sedimentary basin of the Northwest Territories (Craig, 1965).

Similarities of orientation between joints observed in the Precambrian rocks of northeastern Alberta and of the Fort McMurray area are immediately obvious (figure 33). The question remains whether this similarity in orientation implies a common origin. Alternative

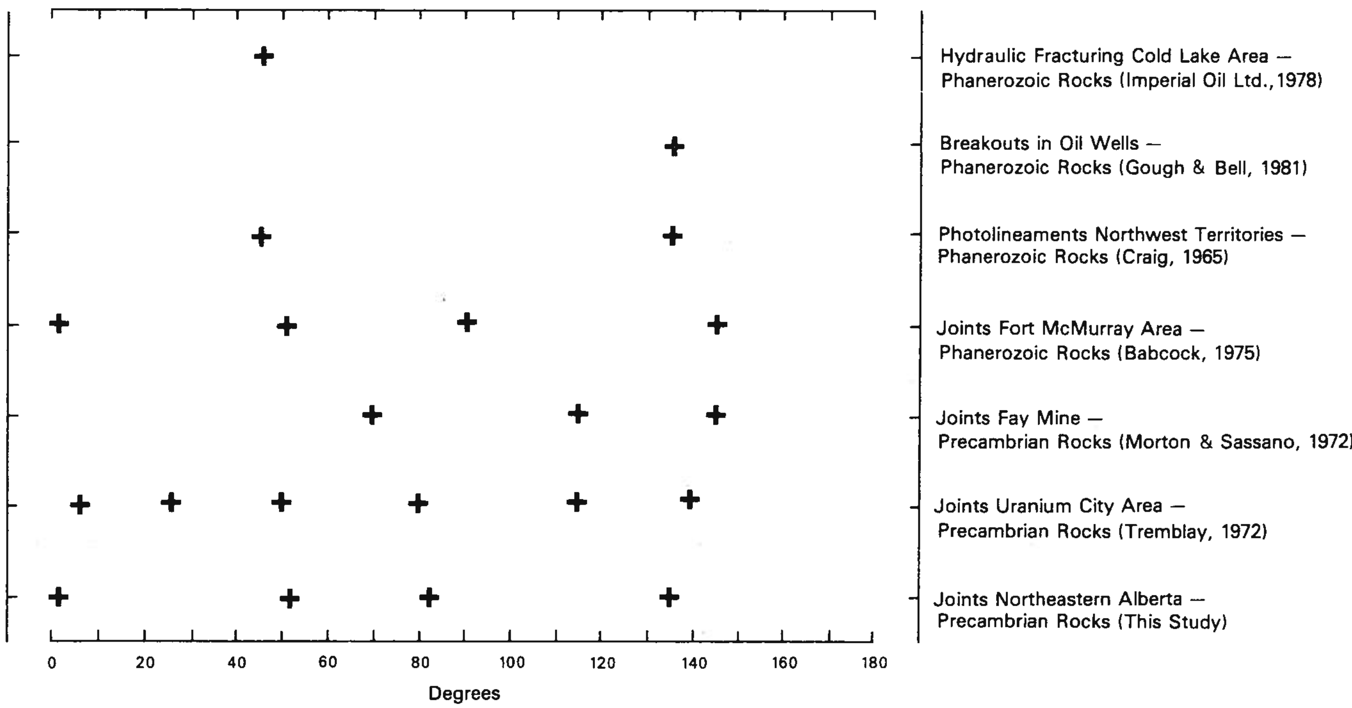

Figure 33. Summary of fracture and lineament orientations in Precambrian and Phanerozoic rocks from northern Alberta (including data from adjoining areas).

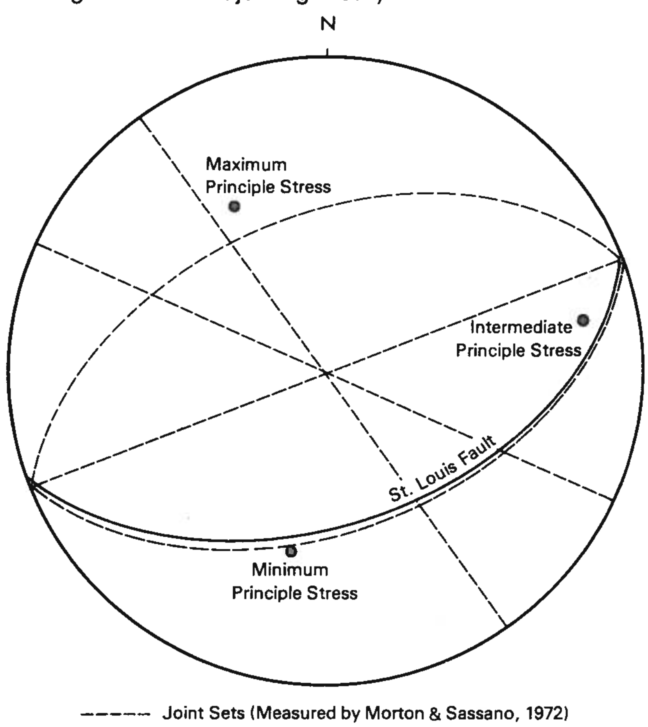

Figure 34. Lower hemisphere equal area projection of the principal stresses measured in the Beaverlodge Mine, Eldorado Nuclear Limited (northwestern Saskatchewan). The orientation of the St. Louis Fault and joints is shown.

explanations may involve the repeated operation of similar stress fields, or a later influence of the earlier established underlying Shield joints.

In this context, two studies of subsurface fractures in oil wells are of interest (Babcock, 1978; Gough and Bell, 1981). Many oil wells in Alberta and northeastern British Columbia exhibit spalling of the walls (known as breakouts), which elongates the holes with the longer axis aligned NW-SE (figure 33). Babcock (1978) proposes that the breakouts might be controlled by pre-existing joints encountered by the drill. If this were the case, breakouts could also be expected parallel to the NE-SW, E-W and N-S striking joints. This is not observed. Gough and Bell (1981) conclude that these breakouts are produced through stress concentration near the hole walls in a stress field having large unequal, horizontal principal stresses and with the larger compressional axis oriented NE-SW.

Another indication of this type of horizontal stress field comes from steam-injection fracturing in the Cold Lake area (Imperial Oil Ltd., 1978). Steam is injected into bitumen-saturated sands. Interwell secondary permeability is established after vertical fractures form. In the early Ethel Pilot Plant, interwell communication is established at N45°E. In the later Leming Pilot Plant, the principal directions of communications are in the general NE direction at angles of N16°E and N76°E. There is also one orientation at N44°W, approximately orthogonal to the other directions (Imperial Oil Ltd., 1978, question 5). The interwell secondary permeability indicates fracturing induced by the steam injection. Once again, these data support the proposition of a larger horizontal stress axis orientation near NE-SW (Gough and Bell, 1981).

Northeasterly striking joints (Babcock, 1973, 1974, 1975) can now be interpreted as having resulted from strain release in a general crustal stress field having large and unequal horizontal principal stresses. The NW striking joints can be related to this field by rotation of the principal stresses (Price, 1966, p. 135). Consequently, these joints are a relatively recent feature and can occur again whenever strain is released.

Gough and Bell (1981, p. 643) conclude that the present stress field in the Phanerozoic sedimentary rocks is coupled to the regional stress field in the underlying Precambrian basement.

Joint systems in eastern North America, which include observations from the Precambrian Shield, are correlated with a recent regional stress field (Scheidegger, 1978, 1981).

System II joints in the exposed Precambrian Shield of Alberta may now be interpreted as resulting from strain release in a relatively recent regional stress field. This stress field has large, unequal, horizontal principal stresses with the larger compression oriented NE, perpendicular to the trend of the Cordilleran orogen. It is the same stress field responsible for joints, breakouts and hydraulic fracturing in the Phanerozoic cover.

System I joints, which are the most prominent in the exposed Shield of Alberta, cannot be explained by this stress field. Similarly, joints of the Alberta Plains that have a similar N-S and E-W orientation cannot be explained in this manner. Babcock (1973) mentions parallelism of the N-S joints and the Sweetgrass Arch in the subsurface of southeastern Alberta.

In the Precambrian of northeastern Alberta, parallelism of System I joints with prominent N-S and E-W faults is immediately obvious. These faults may determine how the rock will break when strain is released. In this way, the present stress field could have a significant remnant component of the tectonic stress field inherited from a period of intense deformation. Eisbacher and Bielenstein (1971) came to a similar conclusion after studying in situ stresses and joint systems in Proterozoic rocks near Elliot Lake, Ontario. They observed horizontal maximum stress parallel to post-orogenic joints. The in situ stress of the Elliot Lake area is interpreted as remnant tectonic stress that was imprinted onto the rock during the Hudsonian orogeny (1700 m.y. ago). Unloading and reorientation of the tectonic stress was supposedly achieved by long-lived arching along an easterly trending axis.

No in situ stress data are available for northeastern Alberta. The closest source of information is from the Uranium City area (northwestern Saskatchewan). Golder Associates (1980) conducted some in situ measurements for the mine of Eldorado Nuclear Ltd. Nine measurements were attempted in three holes on the 32nd level of the Beaverlodge Mine (Fay shaft area). These holes are within 50 metres of the St. Louis Fault, the major fault of the area. Six measurements were rejected for various reasons that included fractured core, large air bubbles over the strain gauges, and broken electrical leads during overcoring. The results of three accepted measurements are in reasonably close agreement and are used to calculate the principal in situ stresses. The major principal stress has a magnitude of 6920 psi (pounds per square inch) in a direction N331°E and plunging 40°; the intermediate principal stress is 5735 psi in a direction N80°E and plunging 21°; and the minor principal stress is 5270 psi in a direction N190°E and plunging 42°. The directions of principal stress are shown on the stereoplot of figure 34. The orientation of the St. Louis Fault is also represented (dipping 50° in direction N160°E). The five joint sets measured by Morton and Sassano (1972) in the Beaverlodge mine are shown. The major principal stress axis is perpendicular to the St. Louis Fault and parallel to a prominent joint set. Subsequent strain release may have formed the joints parallel and perpendicular to the St. Louis Fault. The three vertical joint sets cannot be explained in the same way by this stress field. They may result from differently oriented stress fields. Unfortunately, other measurements of the regional stress field are not available. The main lesson to be learned from these in situ measurements is that the orientation of the present day stress field may be defined by Precambrian structures, as is the case with the St. Louis Fault.

The orientation of System I joints in the Shield of northeastern Alberta may be explained as strain release in a relatively recent regional stress field that is pre-defined by Precambrian deformations. These deformations had resulted in predominantly N-S striking foliations and N-S and E-W striking faults (see figure 1).

System I joints formed parallel to these various structures. The exact orientation of the stress field during the formation of System I joints is unknown. Similarly, the time of formation of these joints remains uncertain, and it cannot be excluded that System I joints formed during uplift and strain release in the Precambrian, shortly after the Hudsonian orogeny.

Polyphase deformation: a summary

The geological history of the area divides into two principal episodes, occurring in the Late Archean and Aphebian. These episodes are correlated with two generations of structural elements. The older generation (D_1) is confined to Archean rocks and is assigned to the Kenoran orogeny. The younger generation of structures (D_2) is found in both Archean gneisses and Aphebian Granitoids and is assigned to the Hudsonian orogeny (figure 29).

Archean

Field relationships show that the granite gneisses and associated high-grade (partly pelitic) metasediments are the oldest group of rocks in the area. This is substantiated by geochronological work in the Charles Lake area. The pegmatites with an age of about 2500 Ma cut granitoids. Granite gneisses and high-grade metasediments are intruded by these granitoids. This proves the existence of an Archean continental crust composed of ortho- and para-gneisses, and granitoids. The relatively low initial $^{87}Sr/^{86}Sr$ ratio (0.7030) of the pegmatites points to the presence of I-type granitoids derived from igneous source rocks. The initial $^{87}Sr/^{86}Sr$ ratio of the pegmatites is also within the limits for their derivation from mantle-like source material.

The Archean gneisses show tight to isoclinal folding of the foliation on a mesoscopic and macroscopic scale. These folds are older than Aphebian Granitoids and are consequently of Archean age. The older generation of structures (D_1) is correlated with the Kenoran orogeny. The Archean metamorphic minerals, that is hypersthene, sillimanite, spinel, and corundum, are sometimes preserved along foliation planes. They indicate P-T conditions during deformation D_1 of $P = 7.5 \pm 2$ kbar and $T = 900 \pm 100$ °C. These are in the granulite facies P-T field.

Aphebian

As discussed earlier, observations indicate that the Athabasca Mobile Belt is comprised of reactivated material from the Archean basement. Large-scale heating of this basement resulted in anatexis, formation of S-type granitoids and diapiric doming. Numerical techniques are shown to be strong tools in delineating the dome and basin geometry of the remobilized terrain. Parts of the domes and basins can be shown to form statistically cylindrical domains. This allows cross-sections to be constructed by down-plunge projection. Some of these domains fit a conical fold model.

Doming of the granitoids is correlated with domal D_2 structures in the Archean basement gneiss complex. The doming is dated by the ages of the S-type granitoids and is about 1900 Ma old. Co-existing metamorphic minerals in enclosed high-grade metasediments indicate that the doming occurred under moderate pressure granulite facies conditions ($P = 5 \pm 0.7$ kbar, $T = 740 \pm 30$ °C). The model of diapiric doming is preferred over a fold interference model. Arguments in favor of this model include: the granulite facies environment, a lack of preferred orientation of the domes and basins, and the intrusive relationships between Aphebian granitoids and Archean gneisses. Most domes are immature diapirs. The Wylie Lake dome may represent a more advanced stage of diapirism. The higher metamorphic grade in the Tulip Lake area may indicate that doming continued longer in this area than in the surrounding terrain. However, it did not attain a mature stage of diapirism. Anatexis and diapiric doming results from a high heat flow some 500 km inland from a major subduction zone, the remnants of which are now in Saskatchewan.

Subsequent faulting along large-scale shear zones is dated at about 1700 Ma. Mylonites point to a ductile style of deformation in the shear zones. Still younger movements along the numerous faults are of a more brittle character.

Joints in northeastern Alberta, which are also a brittle fracture phenomenon, can be grouped in two systems. Each system consists of two orthogonal sets. System I, which is the most prominent, has sets striking roughly north-south and east-west. These directions parallel many faults and consequently this system may have formed from strain release in a relatively recent stress field defined by Precambrian deformations. These joints may, however, be much older. They could have formed in the Precambrian.

System II has sets striking NE-SW and NW-SW. Although these sets also parallel some faults, this system is thought to have originated in a more extensive regional stress field. A stress field with large, unequal horizontal principal stresses exists in Phanerozoic rocks of the western Canadian sedimentary basin. The larger compressional axis is oriented northeast-southwest. This stress field has resulted in breakouts in oilwells, steam-injection fracturing, and northeasterly striking joints. Northwesterly striking joints in Phanerozoic rocks may be related to this stress field upon rotation of the principal stress axes. System II joints in the exposed Precambrian Shield in Alberta are interpreted as resulting from the same regional horizontal stress field that caused the NE and NW striking joints in the Phanerozoic cover.

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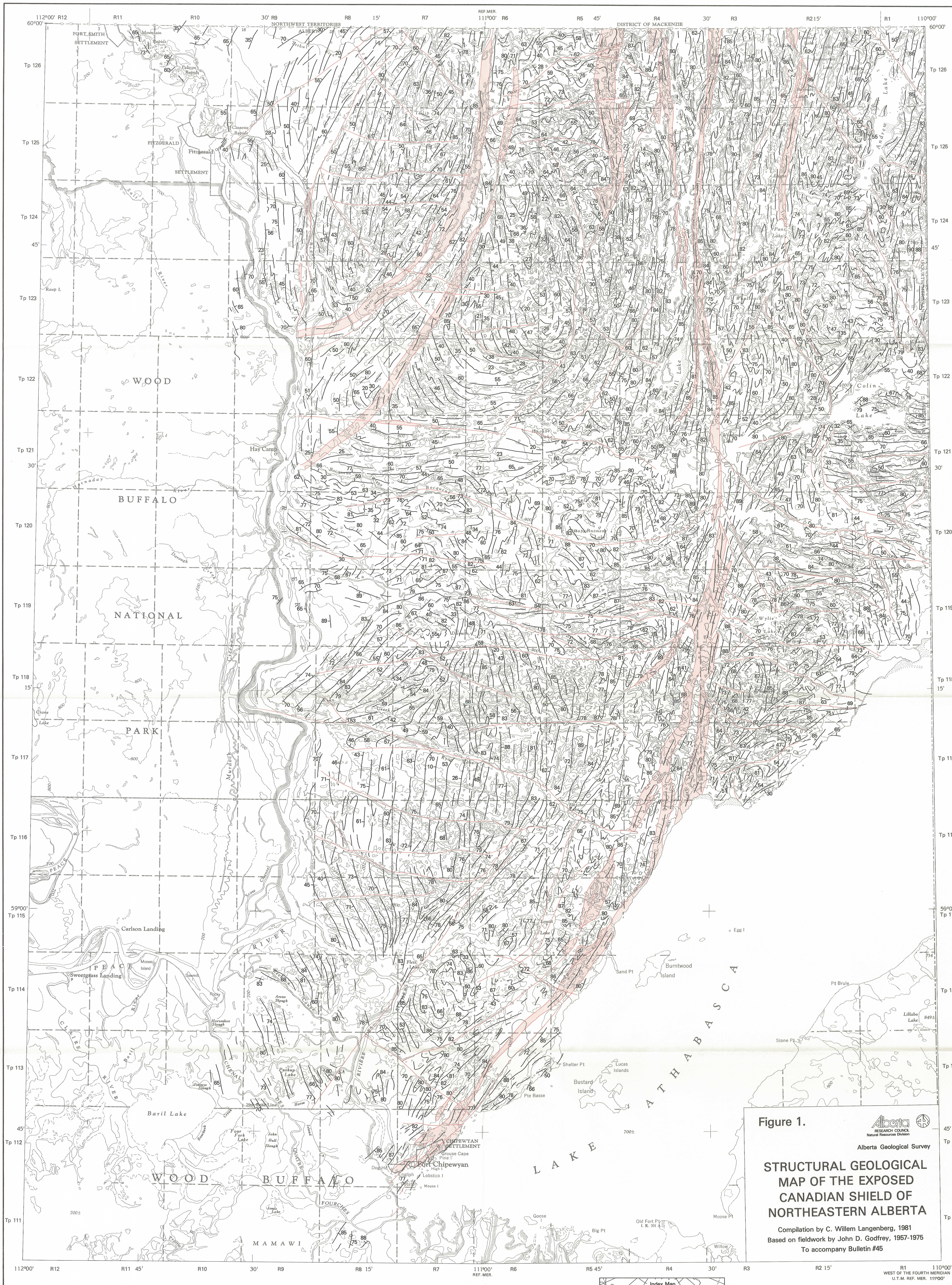

Figure 1.

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Alberta Geological Survey

STRUCTURAL GEOLOGICAL MAP OF THE EXPOSED CANADIAN SHIELD OF NORTHEASTERN ALBERTA

Compilation by C. Willem Langenberg, 1981
Based on fieldwork by John D. Godfrey, 1957-1975
To accompany Bulletin #45

Base map obtained from the Surveys and Mapping Branch, Department of Energy, Mines and Resources, Ottawa, NTS 74L and 74 M, 1957

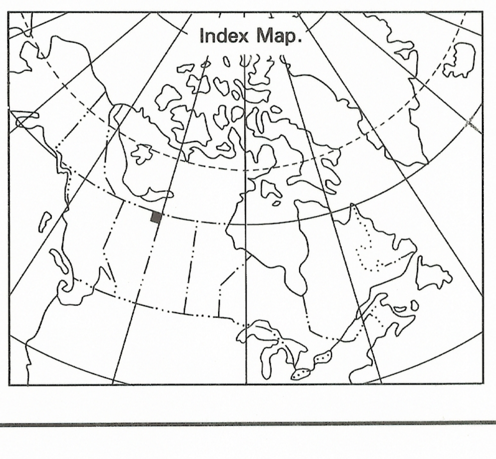
Map drafted by Drafting Services, ARC.

Magnetic declination 1983 varies from 26°19' easterly at centre of north edge to 25°02' at centre of south edge. Mean annual change 4.2' westerly

Published 1983

Scale 1:250,000

0 5 10 15 20 25 kilometres
0 5 10 15 miles



Legend

67 Foliation trend (showing dip direction and dip)

Shear zone

Fault

Figure 30.

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Natural Resources Division

Alberta Geological Survey

SMOOTHED ROSE DIAGRAMS OF JOINTS PER TOWNSHIP IN NORTHEASTERN ALBERTA

Compilation by C. Willem Langenberg, 1981
Based on fieldwork by John D. Godfrey, 1957-1975

To accompany Bulletin #45

Base map obtained from the Surveys and Mapping Branch,
Department of Energy, Mines and Resources, Ottawa, NTS 74L and 74 M, 1957

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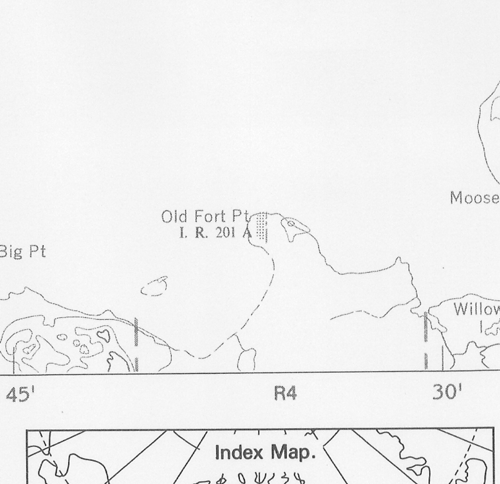
Published 1983

Scale 1:250,000

0 5 10 15 20 25 kilometres
0 5 10 15 miles



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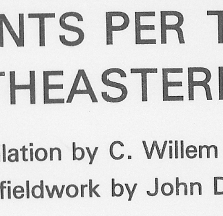

Smoothed rose diagram. The circle represents a uniform distribution.

N = 25 Number of joint measurements