Surface Geology and Structure of the Kotaneelee Anticline, Fort Liard Area, N.W.T.
(Exploration Licence No. 379)

A study carried out for

Norcen Energy Resources Ltd.

July - September, 1996

by

Thomas E. Kubli, Ph.D., P.Geol.

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T2M3E5

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SUMMARY OF SURFACE GEOLOGY AND STRUCTURE OF THE KOTANEELEE ANTICLINE, FORT LIARD AREA, N. W. T.

Exploration License 379 on Kotaneelee Anticline, Fort Liard area, Northwest Territories, was granted to Norcen Energy Resources Limited on April 10, 1996. In order to evaluate the Devonian gas prospectivity on the feature, Norcen acquired a 111.9 square kilometer 3D program in the summer of 1996. During this same time period, Norcen hired a consulting geologist, Thomas Kubli of TEK Consulting Ltd., to conduct a geological mapping project over the license and the immediate surrounding area. The purpose of this work was three fold: (1) to accurately determine the geometry of the Kotaneelee Anticline, (2) to gain an insight into the structural style of the area and most importantly (3) to provide accurate maps and cross sections for use in the 3D seismic interpretation.

The report is divided into two parts - stratigraphy and structure. The stratigraphy of the area includes the Besa River Formation (U. Devonian-Mississippian) within the core of the anticline to the Fort St. John Group (Lower Cretaceous) along the flanks of the anticline in the valley bottoms. The structural discussion involved the geometry of the Kotaneelee Anticline, statistical analysis of bedding data, detachments and detachment levels, faulting and fracture systems. Over most of its length, the Kotaneelee Anticline verges to the west with a shallow dipping east limb and a steady west dipping to overturned west limb. Both kink and box fold geometrics exist along the length of the structure. From the bedding data, a total of 9 structural domains were identified. From this data, it would appear that the crest of this feature is in the middle of domain 4. Under the detachment discussion, from the box fold geometry and ram restrictions of the various horizons, it was concluded that a major detachment existed at the base of the Besa River Formation. Deeper features could only be identified from the 3D seismic interpretation. Faulting on a significant scale was hoped to be precedent throughout the feature in order to break the Nahanni-Manetoe reservoir into non-communicating compartments. However, from the field work, faulting was not as prevalent as first thought with some of these mapped by Douglas and Norris (1959) and Douglas (1974) were found not to exist at all as have very minor displacement.

T. Kubli constructed a 1:50,000 map consisting of the various lithologic units and stratigraphic contacts. This map was digitized in-house and used in conjunction with the 3D survey plan to arrive at an integrated geological-geophysical interpretation of the exploration license. Unfortunately the 3D interpretation of the block suggests that the calumniation of the Kotaneelee Anticline on this exploration license has now been evaluated.

No further work is planned by Norcen on E. L. 379. Norcen's total costs for this study were $30,805.79.

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Summary

The Kotaneelee Anticline is a large-scale detachment fold located in the southern Franklin Mountains, 50 km northwest of Fort Liard, N.W.T. It is cored by shales of the Upper Devonian - Mississippian Besa River Formation. The depth of a shallow detachment was calculated to lie at the base of that formation, which is some 1700 m thick. Strata involved in the folding also include the Mississippian - Permian Mattson Formation, the Permian Fantasque Formation and the Lower Cretaceous Fort St. John Group.

Detailed mapping and analysis of outcrop data show the structural style to be that of kink folding, with domains of constant dips being separated by distinct boundaries. The Kotaneelee Anticline verges to the west over almost its entire length, except for the southernmost portion, which verges to the east. In the study area, the fold has a near-vertical west limb and an east limb with relatively shallow dips. North and south of exploration license No. 379 (held by Norcen), it has a distinctive box fold geometry, with a portion of the east limb dipping steeply to the east.

Statistical analysis of bedding orientations suggests an axial culmination of the Kotaneelee Anticline in the central portion of the study area. The hinge region of the fold reflects this culmination only to a minor degree. It is expressed mostly in a change of the fold geometry and the warping of the more shallowly dipping east limb.

Sinuous axial trends and variations in orientation between separate structures are observed regionally. They could be the result of two phases of deformation, the latter under a transpressional tectonic regime (Richards 1969). Alternatively, a compressional phase of deformation could have overprinted a pre-existing pattern of northeast and northwest trending strike-slip faults (Gabrielse, 1966).

Transitions from the main part of the Kotaneelee Anticline to adjacent structures, both to the north and the south, are left-handed en echelon steps from southeast to northwest. They are not consistent with a right-handed pattern established regionally in the Mackenzie Mountains (Norris, 1985).

Steep, west-directed reverse faults of great lateral extent and some minor east-directed thrust faults are shown on reconnaissance maps by the Geological Survey of Canada (Douglas, 1974). However, their existence could not be confirmed by this study, and faulting seems to be much less common than previously thought.

Fracture orientations in the Kotaneelee Anticline are similar to those of a generalised theoretical model. Fractures are perpendicular to bedding. Two sets of extensional fractures occur, a dominant *ac* set and a subordinate *bc* set. Two sets of *hk0* fractures possibly form a Type II conjugate pair.

Introduction

Study area

The study area is located 50 km northwest of Fort Liard, N.W.T., covering part of the Kotaneelee Anticline between lat. 60°20' and 60°35', and long. 124°05' and 124°15', (Figure 1). Mapping for this study covers exploration license No. 379, currently held by Norcen, and immediately surrounding areas.

Purpose

The Purpose of this study is:

a) to accurately determine the geometry of the Kotaneelee Anticline,
b) to gain an insight into the structural style of the area, and
c) to provide accurate maps and cross-sections for use in seismic interpretation and processing, as well as for regional structural interpretation.

Method of Study

The study area was mapped at a scale of 1:50,000 (Figure 2). Lithologic units and stratigraphic contacts were identified in traverses run across strike and were then traced along strike, both on the ground and through air photo interpretation. Stratigraphic divisions were based on and modified from mapping carried out by Douglas and Norris (1959) and a later compilation map (Douglas, 1974). On the geologic map (Figure 2), nomenclature established by the G.S.C. (Douglas, 1974) was maintained and supplemented with newly introduced units. Contacts mapped by Douglas (1974) outside the study area were modified through air photo interpretation.

Bedding attitudes and fracture orientations were measured in outcrop and entered with brief lithologic descriptions in a Microsoft Excel ® spreadsheet. Further processing was carried out using Gaiabase ® software. Digital files in both formats are supplied with this report (Supplement I). Mean bedding orientations for each field measuring station were plotted on a separate map (Figure 3) and representative measurements were transferred to the geologic map (Figure 2). Structural domains were determined based on geometry and position of structural elements and to obtain close approximations to cylindrical geometries. Cylindrical fold axes were then calculated for each domain and used for projection into cross-sectional planes.

Five cross-sections at a scale of 1:50,000 were constructed to illustrate fold geometries and their variations along strike (Figure 4).

Fracture orientations were compiled separately for the east and the west limb of the Kotaneelee Anticline and were plotted on equal area diagrams for further analysis.

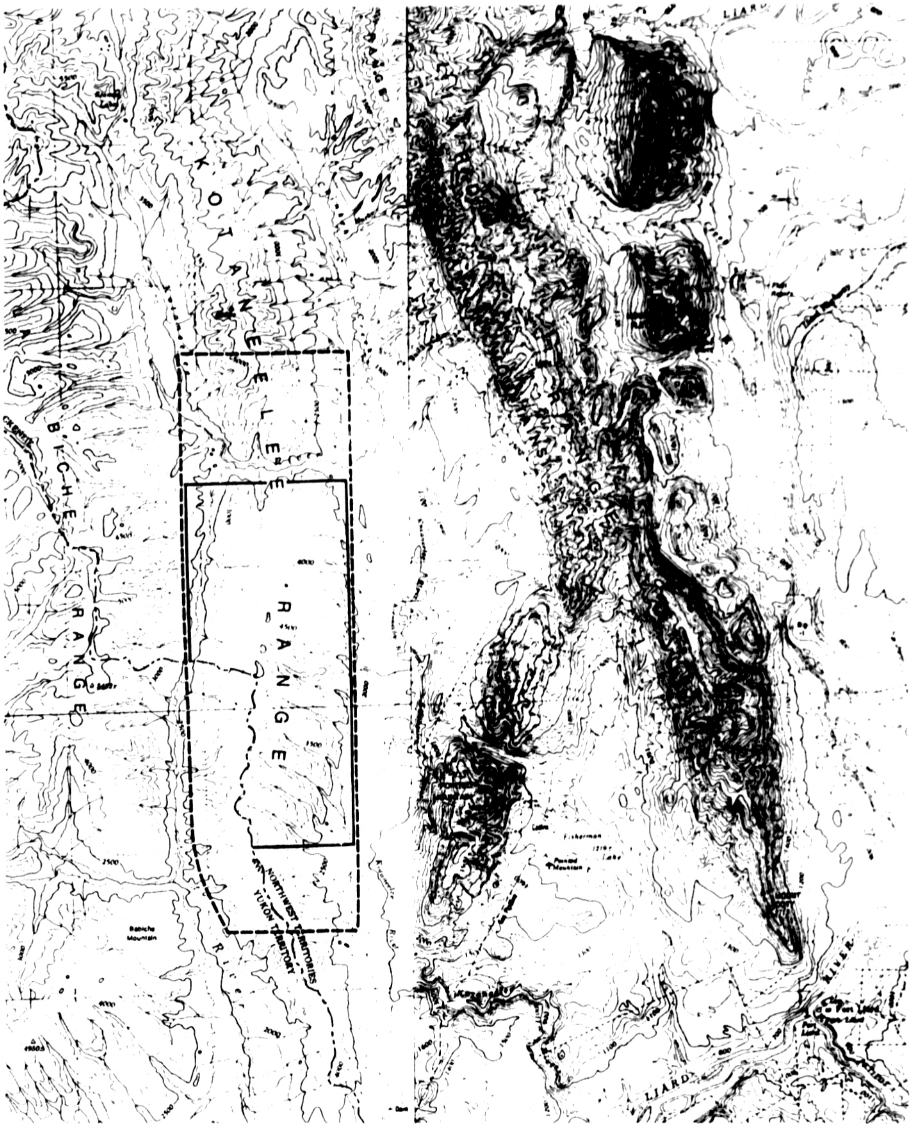

Figure 1: Location map showing study area (dashed outline) and exploration licence # 379 (solid outline), currently held by Norcen.

Stratigraphy

Most outcrops in the Kotaneelee Anticline consist of strata of the Carboniferous and Permian Mattson Formation. The oldest exposed rocks in the core of the anticline are dark shales of the Devono-Mississippian Besa River Formation. On the flanks of the anticline, the Mattson Formation is overlain by the Permian Fantasque Formation and possibly some rocks of Triassic age. Lower Cretaceous strata of the Fort St. John Group occupy the valley bottoms, both to the east and west of the Kotaneelee Range, and form the cores of the La Biche and Kotaneelee synclines.

Besa River Formation

(Upper Devonian and Mississippian)

The Besa River Formation consists mainly of dark grey to black shales with iron-stone concretions. Minor interbeds of sandstone, siltstone and argillaceous limestone can be found in the upper part of the formation (Douglas and Norris, 1959; Figure 5).

The Besa River Formation forms the core of the Kotaneelee Anticline at the surface. Outcrops are sparse and restricted to very few creek exposures and river cuts. The best exposure is found immediately north of the Kotaneelee River, at Kotaneelee Gap, where the river crosses the surface anticline (Figure 5). Douglas and Norris (1959) measured approximately 600 m of Besa River strata at this location. Total thickness in the study area is estimated at 1500 - 1750 m (Douglas and Norris, 1959; Douglas, 1974).

The Besa River Formation varies greatly in its stratigraphic limits. Shales of the upper part of the formation have been identified as stratigraphic equivalents of the Mississippian Flett Formation (Douglas and Norris, 1959). Some resistive beds can be recognised on air photographs within the Besa River Formation, in the east limb of the anticline. They may represent limestones or calcareous sandstones equivalent to the Flett Formation, which was encountered in the Pan Am Kotaneelee O-67 well and whose western edge is interpreted to underlie the east limb of the Kotaneelee Anticline (Douglas, 1974).

Mattson Formation

(Carboniferous and Permian)

The Mattson Formation consists of interbedded shales, sandstones and limestones and represents an overall shallowing-upward magacycle. It has been subdivided into a lower, middle and upper unit, based on the predominant lithology (Douglas and Norris, 1959).

The thickness of the Mattson Formation, estimated from cross-sections (Figure 4), ranges from 1650 m to 1750 m. This is considerably thicker than the 1250 m shown in cross-sections of the Kotaneelee Range by Douglas (1974) and the 1130 m measured at Mattson Gap on Liard Range (Douglas and Norris, 1959). Some of this discrepancy may result from uncertainty in placing the Besa River - lower Mattson and the upper Mattson - Fantasque contacts. However, projected bedding measurements and mapped contacts give some confidence in estimates from the cross-sections in this report, keeping in mind that no complete stratigraphic section has been measured in the Kotaneelee Range. Thus, some westward stratigraphic thickening has to be inferred. This is supported by Douglas and Norris (1959) reporting the greatest measured thickness (1400 m) from Tika Creek in the west limb of the Fantasque Syncline, some 40 km northwest of the study area.

Lower Mattson Formation

The lower Mattson Formation is characterised by dark grey shales with 10 - 20m intervals of siltstones and sandstones (Figure 6). The shales are indistinguishable from the underlying Besa River shales. Sandstones are light to dark grey, yellow to buff to red weathering and mainly fine-grained and thinly bedded with a "flaggy" appearance in outcrop (Figure 7). They are partly carbonaceous and locally cross-bedded. Intervals of greenish to yellow weathering siltstones are common. Douglas and Norris (1959) reported silty carbonaceous shale and coal seams near the top of the unit. Some interbeds of very resistive, fine grained, white to red weathering quartzarenite, friable sandstones with large-scale cross-beds and calcareous sandstones occur in the lower Mattson Formation. However, these lithologies are more typical of the middle Mattson Formation. The thickness of the lower Mattson Formation, estimated from cross-sections, ranges from 550 m in the north of the study area to 650 m in the south.

Middle Mattson Formation

The middle Mattson Formation is characterised by alternating recessive and resistive zones that represent intervals of shales and sandstones. Compared to the lower Mattson Formation, the shale intervals are thinner, and the unit as a whole is sandstone-dominated, more resistant and cliff-forming (Figure 8). The thickness of the middle Mattson Formation, estimated from cross-sections, ranges from 440 to 640 m.

The lower part of the unit is dominated by 5 to 20 m intervals of light grey, thin- to medium-bedded quartzarenites, partly with low-angle cross-stratification. They are fine- to medium-grained and well sorted, to give a quartzite-like appearance in outcrop. Weathering colours are brown, or more typically white to orange-red.

Friable Sandstone Unit

The overlying "friable sandstone unit" was mapped on the east limb of the Kotaneelee Anticline and could be traced over most of the length of the study area. It is placed in the upper part of the middle Mattson Formation, based on the predominance of sandstones. Sandstone intervals are 5 to 20 m thick (Figure 9) and consist of well-sorted, fine- to medium-grained, light grey to yellow quartz arenites. Bedding is medium to thick, and high-angle trough cross-bedding is predominant (Figure 10). Thinly bedded, sandstones, partly fossiliferous sandy limestones and calcareous sandstones occur in shale dominated recessive intervals between the sandstones.

The sandstones are moderately to extremely friable, with some outcrops deteriorating into piles of sand. Their weathering colour is typically white but can locally vary to yellow, orange and brown. These latter colours are probably caused by hematite that is commonly present in the unit. The friability is possibly due to surface leaching of a carbonate matrix and/or cement, and the extremely high porosity of these sandstones most likely does not extend more than a few metres below the surface.

Friable sandstones that are indistinguishable from the ones in the middle Mattson Formation also occur to a lesser extent in the upper Mattson Formation. Based only on its stratigraphic and structural position, one relatively thick interval ocurring at the south end of the study area (domain 6) was assigned to the upper Mattson Formation.

Upper Mattson Formation

The upper Mattson Formation is relatively recessive. It consists of interbedded fossiliferous limestones, fine-grained calcareous sandstones, sandstones, sandy dolomites, argillaceous limestones and dark, fissile, concretionary shales. The transition from the middle Mattson Formation is gradational, and the boundary was mapped where prominent cliff-forming sandstone intervals are no longer present and mixed carbonate-clastic lithologies become more common.

Fossil debris, mostly brachiopod and crinoid fragments, are very common in this unit, while whole fossils are very rare. Most units are through cross-bedded, including the ones containing abundant fossil debris (Figure 11). These features are all indicative of a high-energy environment with abundant reworking of transported constituents.

The thickness of the lower Mattson Formation, estimated from cross-sections, ranges from 450 m to 625 m.

Calcareous Unit

On the east limb of the Kotaneelee Anticline, a calcareous unit was mapped in the upper part of the upper Mattson Formation. It is characterised by the predominance of relatively pure limestones and dolomites as opposed to the lower part of the upper Mattson Formation that has more of a clastic component. Lithologies range from crinoidal packstone to mudstone to argillaceous mudstone. Brachiopods, corals and bryozoans are locally abundant in the limestones (Figure 12).

This unit was further subdivided into a *lower calcareous unit*, characterised by medium to dark grey limestones and sandy, cross-bedded limestones, and *an upper calcareous unit* with thinly to medium-bedded, buff weathering, light grey lime-mudstones and sandy lime-mudstones. Close to the transition to the overlying Fantasque Formation, the upper unit contains beds with abundant, unbroken brachiopod shells.

Conditions of Deposition

The lower to middle Mattson interval displays a pattern of decreasing water depth and increasing energy in a dominantly clastic setting. The shale-dominated lower Mattson may represent a transition from a prodelta slope to a delta front or distal mouth bar with influx of fine grained sandstones and siltstones.

The dominance of thick intervals of large-scale cross-bedded sands in the middle Mattson indicates a high energy setting in a barrier beach complex or a related strand plain setting. Locally occurring high-angle trough cross-beds may represent backshore dunes.

Increased occurrence of limestones and the presumed calcareous matrix of the "friable sandstone unit" in the upper half of the middle Mattson indicate increased carbonate production nearby with simultaneous reworking in a high energy setting. This trend continues in the upper Mattson, where carbonate production becomes dominant and clastic influx is subordinate. A carbonate platform may have been established during deposition of the lower calcareous unit.

The increased deposition of fine grained sand, together with carbonate mud, the absence of indications for a high energy environment in the upper calcareous unit, and finally the deposition of siltstones in the uppermost Mattson indicate increasing water depth.

Fantasque Formation

(Permian)

The chert of the Fantasque formation is reported by Douglas and Norris (1959) to be 45 m thick, but in the Kotaneelee Range may be as thin as 20 m. It consists of bedded and laminated, partly greenish weathering, light and dark grey chert (Figure 13). It is partly sandy with remnants of sandstone and dolomite (Douglas and Norris, 1959).

At Kotaneelee Gap, in both limbs of the anticline, the chert is underlain by partly cherty siltstones (Figure 14). The thickness of this siltstone unit could not be established due to a lack of exposure. In the east limb of the anticline, it seems to be absent farther south, where chert directly overlies limestones of the upper calcareous unit. Since the Mattson - Fantasque contact is reported to be unconformable (Douglas and Norris, 1959), it appears more likely that the siltstones have to be included in the upper Mattson Formation.

The chert is overlain by fine-grained, grey, mottled sandstones and mudstones. Douglas and Norris (1959) included them in the Fantasque Formation due to their close association with the chert.

The Fantasque Formation thins toward the north underneath the pre-Cretaceous unconformity. Its zero edge is immediately north of the study area, where Lower Cretaceous rocks directly overlie upper Mattson strata.

Triassic (?) Unit

In the central and southern part of the study area, the chert is overlain by interbedded shales, bioturbated siltstones and fine grained sandstones with abundant *Zoophycos*. These strata could be Permian in age and correspond to the above mentioned mottled sandstones and mudstones. However, Douglas (1974) mapped a unit of possible Triassic age, consisting of grey shale and thinly bedded siltstone, in the same stratigraphic and physical position. On the geologic map of Figure 2, the unit is shown as possibly Triassic. Further biostratigraphic work is needed to make a definite age assignment.

Fort St. John Group

(Lower Cretaceous)

Lower Cretaceous rocks unconformably overlie Permian strata in the study area. They were not examined in this study. Detailed descriptions can be found in Douglas and Norris (1959), Stott (1960) and Richards (1969). The Garbutt, Scatter, Lepine, Sikanni and Sully formations (in ascending order) constitute the Fort St. John Group and are shown on the geologic map essentially as mapped by Douglas (1974).

A conspicuous thinning of the Garbutt Formation on the east limb of the Kotaneelee Anticline was ascribed both by Stott (1960) and Douglas and Norris (1959) to an east-directed reverse fault. However, there is no evidence for such a fault at surface or in seismic sections. In the structural cross-sections, the thinning is thus interpreted as stratigraphic (depositional or erosional).

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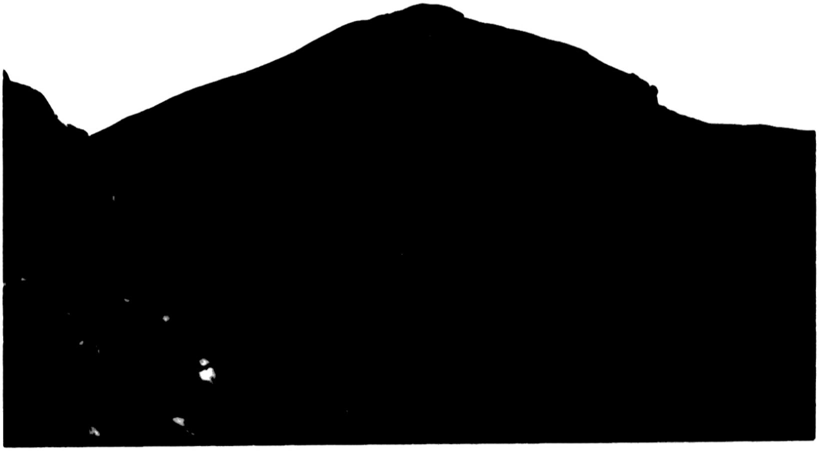
Figure 7: Thinly bedded quartzarenite of the lower Mattson Formation.



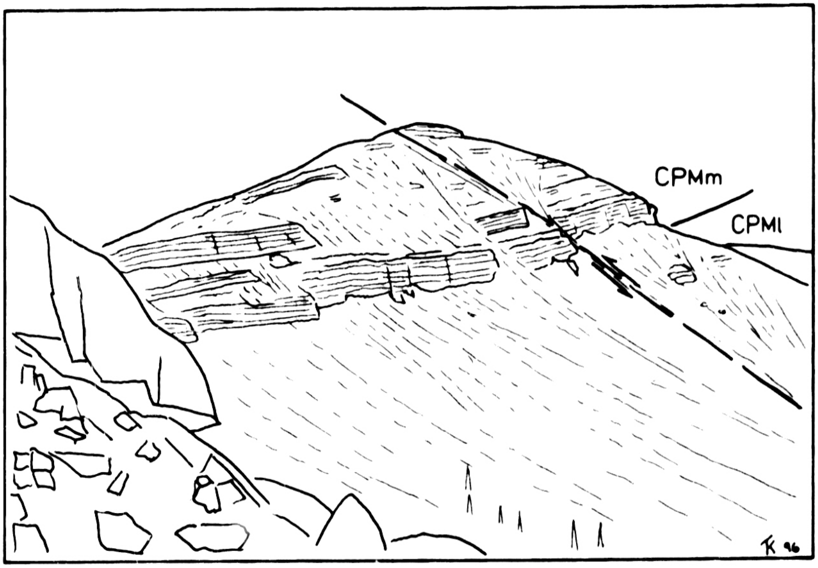


Figure 8: Cliff-forming quartzarenites of the lower part of the middle Mattson Formation. Note transverse fault with small offset. View to the southeast. (Stn. 15 b, UTM 435850/6705830).

Figure 9: A 10 m cliff, formed by sandstones with high-angle through cross-bedding, in the "friable sandstone unit".

Figure 10: Typical "friable sandstone" with high-angle trough cross-bedding. (Lens cap for scale is 5 cm).

Figure 11: Cross-bedded sandy dolomite of the upper Mattson Formation with abundant fossil debris. (Lens cap for scale is 5 cm).

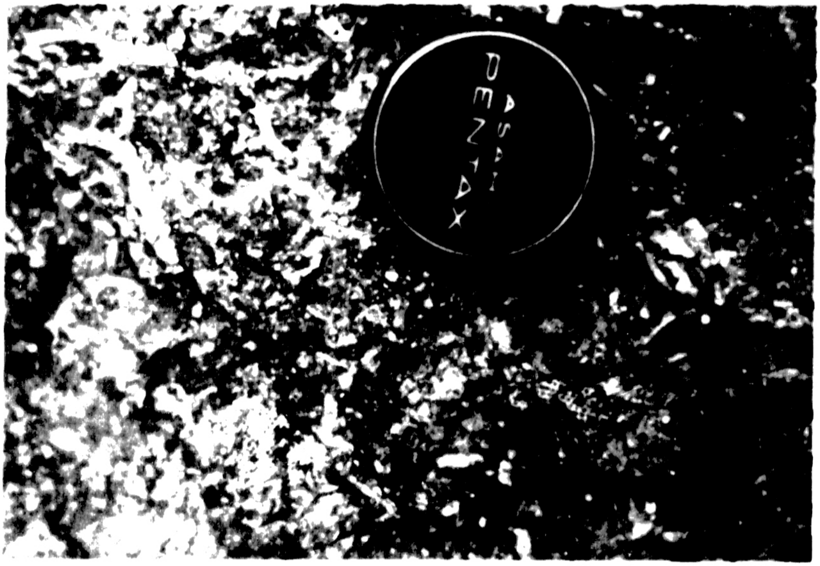


Figure 12: Limestone of the "calcareous unit" in the upper Mattson Formation, containing abundant bryozoans and corals. (Lens cap for scale is 5 cm).

Figure 13: Typical outcrop of Fantasque chert in the east limb of the Kotaneelee Anticline. (Stn. 6, UTM 439700/6713925).

Figure 14: Partly cherty siltstones (darker unit behind helicopter) underlying the cherts of the Fantasque Formation. West side of Kotaneelee Gap (Stn. 19a, UTM 431950/6718690).

Structure

Regional Setting

The Kotaneelee Anticline is one of several large-scale detachment folds that constitute the southern Franklin Mountains at the transition from undeformed foreland to the Liard Plateau of southern Mackenzie Mountains (Figure 15). It is roughly 75 km long and 10 km wide and is one of the longest folds compared to similar structures of the area. The regional structural grain of the southern Franklin Mountains is approximately north - south, whereas, to the north, the structures of the Franklin and Mackenzie Mountains describe an arcuate pattern with gradually more westerly strikes (Figure 15).

The axial planes of these folds are typically warped around fold axes that plunge steeply to the west or east, resulting in a sinuous map pattern. In the Liard Range, east of the study area, two distinct axial trends (northeast-southwest and northwest-southeast) are present. Richards (1969) interpreted these variations in axial trends as the result of a dextral transpressional regime, caused by differential movement between the Rocky Mountains in the south and the Mackenzie Mountains in the north. This regime would have been active during the later phases of deformation in the Rockies, while compression was no longer active in the Mackenzie Mountains. In the southern Franklin Mountains, this would have resulted in two consecutive phases of deformation, each with a different orientation of the main compressional stress.

Interpretations for surface structures in the northern Franklin Mountains and the Colville Hills suggest a shallow response to deep seated wrench faults (Cook, 1983), and transcurrent movements of basement blocks have been reported to influence folding in the Mackenzie Mountains (Gabrielse, 1966). A similar interpretation could be applied to the southern Franklin Mountains. A pre-existing pattern of northeast and northwest (?) trending strike-slip faults, overprinted by one prolonged phase of shortening could have been sufficient to cause the warping of axial planes.

Neither of these interpretations can be confirmed or disputed in this study. The question of what caused the warping of axial planes has to be investigated on a more regional scale.

The transitions from the Kotaneelee Anticline to the Etanda Dome in the north and from the central portion of the anticline to its southernmost extremity at Mt. Martin are en-echelon steps through synclines, from southeast to northwest. This left handed sense of offset is not consistent with patterns observed regionally by Norris (1985), who reported right handed en-echelon offsets in the southern, north-south striking part of the Franklin and Mackenzie Mountains.

Geometry of the Kotaneelee Anticline

The alternation of shale and sandstone intervals of the stratigraphy involved in the Kotaneelee Anticline facilitated flexural slip folding and the development of parallel folds. A relatively low amount of shortening in the area has led to generally broad, open fold geometries. Details of fold geometry are shown in the cross-sections of Figure 4, and along-strike variations of the southern portion of the Kotaneelee Anticline are illustrated in a schematic diagram (Figure 16).

Over most of its length, the Kotaneelee Anticline verges to the west, with a shallow east limb and a steeply west-dipping to overturned west limb. Cross-sections of Douglas and Norris (1959) and Douglas (1974) depict the Kotaneelee Anticline as a rounded, parallel fold. However, field observations and systematic measurement of bedding attitudes document the existence of distinct domains of constant dip, separated by sharp kinks (dip domain boundaries).

North of Kotaneelee Gap, the Kotaneelee Anticline is a box fold (cross-section A - A'). The east limb steepens toward the core of the fold (Figure 17), and three dip domains (18°, 25° and 60° - 80°) can be recognised (Figures 2 and 4). The west limb is near-vertical to slightly overturned (Figure 18). The top of the fold is relatively flat and slightly warped upward. It is separated on both sides from the steep portions of the limbs by sharp monoclinal bends or "kinks" (Figures 19 and 20). Box fold geometries are not unique to the Kotaneelee Anticline. Aerial reconnaissance also identified the Pointed Mountain Anticline to have a box fold geometry with distinct dip domains and kinks.

The steep part of the east limb of the fold is of limited extent along strike. The monoclinal bends at the top and bottom of the steep portion converge, so that immediately south, as well as 13 km north of Kotaneelee Gap, the east limb of the fold has a relatively constant east dip of around 20°.

In the central portion of exploration licence # 379 (cross-sections C-C' and D-D'), the Kotaneelee Anticline is asymmetric, with an east-dipping axial plane, a shallow east limb (Figure 21), a steep west limb and a relatively flat top.

In the southern portion of exploration licence # 379 (cross-section E-E'), a domain of steep dips occurs again in the east limb of the fold. A box fold geometry is developed, and the fold core appears to be verging slightly to the east (Figure 22).

In the southernmost portion of the study area, the Kotaneelee Anticline steps to the southeast in an en-echelon fashion and becomes east-verging. The associated lateral changes in fold geometry are illustrated in Figure 16. Toward the south, the steep west limb of the fold diminishes in height as a new steep dip domain, developed near the fold crest, increases in magnitude. At the same latitude, a steep dip domain is also developed in the easternmost part of the east limb. The resulting fold geometry is shown in Figure 23.

Statistical Analysis of Bedding Data

The study area was subdivided into seven domains, two of which had to be further subdivided after initial analysis (Figure 24). Bedding attitudes were plotted on equal area Pi-diagrams and contoured, where sufficient measurements were available (Appendix I). Best fit cylindrical fold axes were calculated for each domain (Figure 25) and used for projection into cross-sections.

North of Kotaneelee Gap (domain 1), the box fold geometry of the Kotaneelee Anticline was determined to be non-cylindrical. It appears to be conical, opening toward the north. Cylindrical fold axes calculated for each of the monoclinal bends were 003/11 for the east limb and 341/2.5 for the west limb. This is a difference in trend of 22°, diverging toward the north. At the south end of domain 1, the fold geometry changes to cylindrical, which made it necessary to adjust directions for projection into cross-section A - A' (W: 348/05; E: 350/06).

Immediately north of Kotaneelee Gap (domain 2), the fold axis was determined to be near-horizontal (002/02), while domain 3 and the north half of domain 4 yielded moderate northerly plunges (007/05 and 017/05 respectively).

In domain 4 south, the fold axis is essentially horizontal, and in domains 5 and 6 plunges are to the south (183/04 and 143/10). Domain 7 represents an en-echelon step to the east of the fold with a shallow northerly plunge (004/02).

The apparent axial culmination in the southern half of domain 4 is not reflected in the map pattern of the fold core (Besa River - lower Mattson contact). This is partly due to the fact that very few measurements could be taken in the fold core because of poor exposure. Furthermore, the west limb is everywhere near-vertical and has not much influence on the statistically determined plunges. Sampling is thus biased toward measurements taken on the east limb of the fold. The statistically determined culmination is indeed expressed only in the east limb. The fold geometry determined from cross-sections (Figure 4) corresponds well with this observation. Box fold geometries to the north and south (cross-sections A - A' and E - E') place the major part of the east limb at a lower elevation than the asymmetric fold in the centre of the study area (cross-sections C - C' and D - D'). This "warping" of the east limb and associated changes in fold geometry along strike are illustrated in Figure 16.

Detachments

Deep detachment levels have been suggested for the northern Mackenzie Mountains. Depths to detachment have been calculated by Gordey (1981) at 9 km below sea level, and most reports mention involvement of Precambrian strata in folding and a possible detachment in the Upper Cambrian salt (Gabrielse, 1991). Detachment levels seem to be shallower, however, under the southern Mackenzie Mountains and the Franklin Mountains (Gabrielse, 1991).

The box fold geometry of parts of the Kotaneelee Anticline and room restrictions in the core strongly suggest a) detachment folding, and b) the existence of a shallow detachment at a level of the Besa River Formation. A depth to detachment calculation after Epard and Groshong (1993) was carried out, based on cross section A - A'. Depth to detachment was calculated at 1660 m below the top of the Besa River Formation. A comparison of this depth with the estimated total thickness of the formation (1500 - 1750 m), leads to the conclusion that a major detachment exists at the base of the Besa River Formation.

However, this does not exclude that older strata may be involved in folding as well. It only limits the depth to which surface structures can be projected downward to obtain accurate fold geometries.

Thrust or Reverse Faults

Several steeply dipping reverse faults were reported and mapped by Douglas and Norris (1959) and Douglas (1974). However, where they were investigated in this study, some were found not to exist at all. Others were found to have very minor displacements or a vergence different from the one reported by Douglas (1974).

The Kotaneelee Fault

The Kotaneelee Fault was mapped by Douglas and Norris (1959) as a steeply east-dipping reverse fault, running mostly in the Besa River Formation, in the core of the Kotaneelee Anticline. To the north and south, at the plunging extremities of the anticline, the fault was shown to displace strata of the lower and middle Mattson Formation.

North of Kotaneelee Gap, this study revealed the existence of a small, near-vertical, west-side-up reverse (?) fault where Douglas (1974) mapped the Kotaneelee Fault. It coincides with a monoclinal hinge, separating the near-horizontal top from the steep, overturned west limb of the box fold. The fault has an offset of some 20 m and places Besa River strata onto lower Mattson sandstones.

To the south, the Kotaneelee Fault was shown to offset the Besa River / Mattson contact (Douglas, 1974). This could not be confirmed in this study due to lack of outcrop. The fault was also shown to displace the lower to middle Mattson contact. Again, no direct evidence for the existence of this fault could be found in this study.

Other, West-directed Reverse Faults

Douglas and Norris (1959) and Douglas (1974) mapped two parallel, west-directed reverse faults in the west limb of the Kotaneelee Anticline and claim to have seen evidence of these faults at Kotaneelee gap.

A careful examination of outcrops along the Kotaneelee River has shown no evidence for the existence of faults, except for a fault with less than 5 m of west-side - down offset that runs north-south and cuts gently west-dipping cherts of the Fantasque Formation (Stn. 19 a, UTM 431950/6718690). It seems thus that these faults are the product of erroneous air photo interpretation. The west limb of the Kotaneelee Anticline is almost everywhere near-vertical and the monoclinal hinge between the vertical limb and the shallow part of the La Biche Syncline to the west is very sharp where it can be observed in outcrop (Figure 26). Mass wasting phenomena such as slumps and rock falls are prevalent in the west limb of the fold and obscure the geometric relationships in most places. Slumps have to be recognised and carefully examined before any structures can be identified with confidence. Figure 27 shows typical large-scale slumping in the higher parts of outcrops along the Kotaneelee River. These bedding relationships could easily be misinterpreted as faults if the slumping is not recognised.

On the north side of Kotaneelee Gap, a minor west-directed thrust fault with a possible footwall splay was observed in lower Mattson strata, in the east limb of the Kotaneelee Anticline (Figure 28). It cuts bedding at a relatively low angle and appears to have placed a shaley unit on top of a sandstone. The outcrop containing the fault is likely part of a slump block, and the orientation and origin of the fault are therefore uncertain. The fault is interpreted to be the result of bedding-parallel shear, accommodating movement near the monoclinal bend between the shallow and the steep part of the east limb.

East-directed Reverse Faults

A short segment of an east-directed reverse fault was mapped by Douglas and Norris (1959) and Douglas (1974) near the southern termination of the Kotaneelee Fault. Although no evidence for faulting was found in this locality, a small reverse fault may exist, but may be obscured by the en echelon east-stepping of the anticlinal hinge.

An east-directed reverse fault was inferred to run in the Garbutt Formation in the east limb of the Kotaneelee Anticline (Douglas and Norris, 1959; Douglas, 1974; Stott, 1960). It was probably introduced to account for an apparent thinning of the formation over a distance of about 12 km along strike. However, no evidence of the fault can be seen on air photos or seismic data, and the thinning is interpreted to be depositional or erosional.

An east-directed thrust fault was mapped by Douglas and Norris (1959) and Douglas (1974) in the core of the Kotaneelee Syncline. It was not investigated in this study.

Minor Transverse and Oblique Faults

The regional pattern of varying axial trends and its interpretation as an inheritance of wrench faulting would lead one to expect small surface expressions such as strike-slip faults, tear faults and normal faults. Such features do exist to the west of the study area, in the Liard Plateau. Douglas (1974) mapped several northwest-trending normal faults in the east limb of the Fantasque Syncline, and a portion of the Beaver River Fault of westernmost La Biche map area is interpreted as a tear fault (Douglas and Norris, 1959). However, in the study area, no transverse faults with any significant displacement could be found.

Several west to west-northwest striking, near-vertical faults occur locally in the Kotaneelee Anticline. They have very small offsets and are of limited lateral extent. Most of them are either confined to a specific stratigraphic interval or a small portion of the anticline (Figures 4 and 8). It is not possible to determine whether normal or strike-slip movement is predominant on these faults, and there is no systematic pattern of offset sense. The largest vertical offset is estimated at 40 m (Figure 29). In one location, the combination of two parallel transverse faults with slumping has led to significant rotation of strata at the surface (Figure 30). These faults are interpreted as adjustment features in response to differential movement during the formation of the Kotaneelee Anticline.

One transverse fault was mapped over a distance of 10 km (Figure 4). It has a northwesterly strike and cuts the core of the Kotaneelee Anticline obliquely. Offsets in the near-vertical west limb of the fold indicate minor strike-slip displacement. This fault has the same orientation as normal faults mapped in the Fantasque Syncline (Douglas, 1974) and lines up along strike with the oblique, northwesterly striking, northern part of the La Biche Anticline. It is therefore a likely candidate to be connected to a pre-existing pattern of wrench faulting.

Fractures

Due to the limited time and resources available, it was not possible to collect enough fracture measurements for statistical analysis of individual outcrops, individual fracture sets, or specific stratigraphic horizons. However, in most outcrops, one to four distinct fracture sets were recognised, and representative orientations were measured and recorded separately (Supplement I). Sandstone outcrops provided the majority of measurements due to their better exposure. All fracture sets were plotted collectively on equal area Pi-diagrams (Appendix II). In each domain (Figure 24), separate diagrams were constructed for each of the two limbs of the anticline, where the number of measurements was sufficient. In the west limb of the Kotaneelee Anticline, fewer fracture orientations were measured due to widespread slumping of outcrops in that area. Consequently, measurements from adjacent structural domains had to be combined in the Pi-diagrams (one diagram for domains 1,2 and 3, west and one for domain 4, west). The number of fracture measurements from domains 5, 6 and 7 were insufficient for statistical analysis.

Figure 31 Shows a generalised model of fracture orientations relative to a fold. Most fractures are usually oriented perpendicular to bedding, and two main types of fractures can be identified:

Extensional fractures are oriented parallel to the principal directions *a, b* and *c* of the fold. Fractures that are perpendicular to the fold axis (or transverse to the fold) contain the principal directions a and c and are termed *"ac fractures"*. They are a result of extension parallel to the fold axis. Fractures that are parallel to the fold axis contain the principal direction b and c and are thus termed *"bc fractures"*. They are a result of extension in the transport direction parallel to bedding.

Shear joints are oriented as conjugate sets about the maximum stress axis at the time of folding. They are defined as *hk0*, referring to their orientation parallel to the principal direction *c* of the fold (Figure 31; Hancock, 1985). They are oriented obliquely relative to the fold axis. It is common that only one of the two orientations of a conjugate set is present at any given locality. Conjugate sets can be further classified, based on their angle of intersection, which is related to the orientation of principal stresses (Figure 31). Type I sets correspond to extension parllel to the fold axis, and Type II sets correspond to extension perpendicular to the fold axis Stearns (1968)

Fracture orientations in the Kotaneelee Anticline correspond reasonably well with the model of Figure 31. Most fractures are oriented perpendicular to bedding. This is evident from the fact that most poles to fractures plot near the great circles representing calculated mean bedding orientations (Appendix II). Clusters of poles to fractures were identified and labelled on the Pi-diagrams of Appendix II, where possible, using the classification scheme of Hancock (1985)(Figure 31).

The most consistently present extensional fracture orientation is *ac* (Figure 32). Except for the non-cylindrical portion of the fold (domains 1 and 2 combined), the medians of *ac* fracture populations lie within 15° of the calculated axial trend. A systematic counter-clockwise deviation from the ideal *ac* orientation seems to be present.

A *bc* fracture set is also present, but is subordinate to the *ac* set (Figure 32). It can be identified in most east limb domains. In the southern part of the west limb (domains 4, N and S), only two fractures with a *bc* orientation were recorded. No definite fracture pattern can be interpreted in the northern part of the west limb (domains 1 to 3). However, a series of fracture poles of various plunges in the southwest quadrant could be interpreted to represent *bc* fractures with varying dip angles depending to the steepness of bedding dips in the west limb.

Two sets of oblique (*hk0*) fractures are present in most of the area (Figure 34). They are symmetrically oriented about the a and b axes of the fold and could be interpreted as conjugate shear joints. However, slickensides that would identify them as shear joints and indicate the sense of relative movement are typically absent, and their interpretation has to be based on orientation alone. The angle between the two *hk0* sets varies from 51° to 87°, and the acute bisector of the angle is parallel to the b axis. If they are true shear joints, this identifies them as Type II fractures.

The predominance of *ac* fractures suggests extension parallel to the fold axis, wheras the interpreted Type II shear joints and subordinate *bc* fractures suggest extension perpendicular to the fold axis, in the direction of a. This contradiction can be explained in several different ways, none of which are entirely satisfactory:

1) The *hk0* fracture sets do not correspond to conjugate shears, but are extensional fractures, resulting from an earlier phase of deformation with a different orientation of the principal stresses.
2) The *ac* fractures and Type II shears could be the result of two stages of folding, one with net compression and one with extension parallel to the fold axis.
3) Extension occurred both parallel to b and a at the same time, resulting in the axial culmination mentioned earlier (Figure 16).

A more detailed fracture study and the integration of regional structural analysis are necessary to provide a more definitive interpretation.

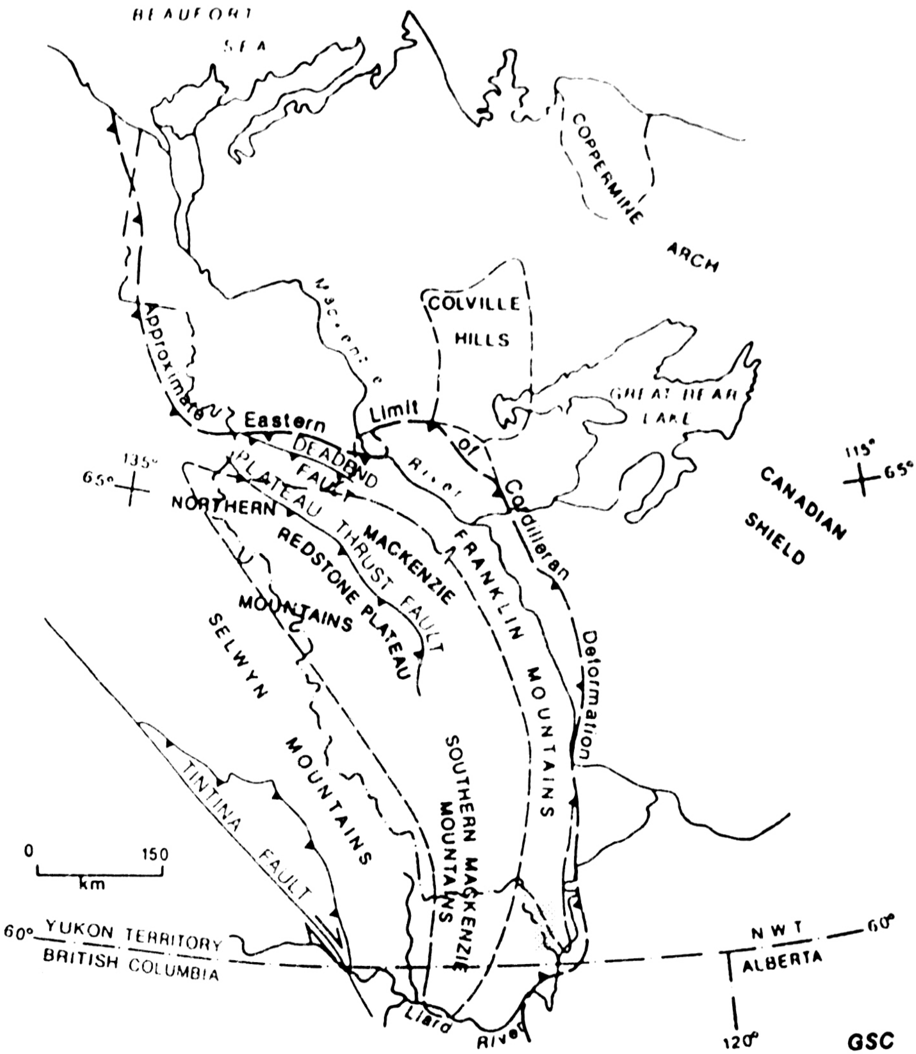


Figure 15: Index map for the eastern part of the Foreland Belt in the Yukon and Northwest Territories. (From Gabrielse, 1991).

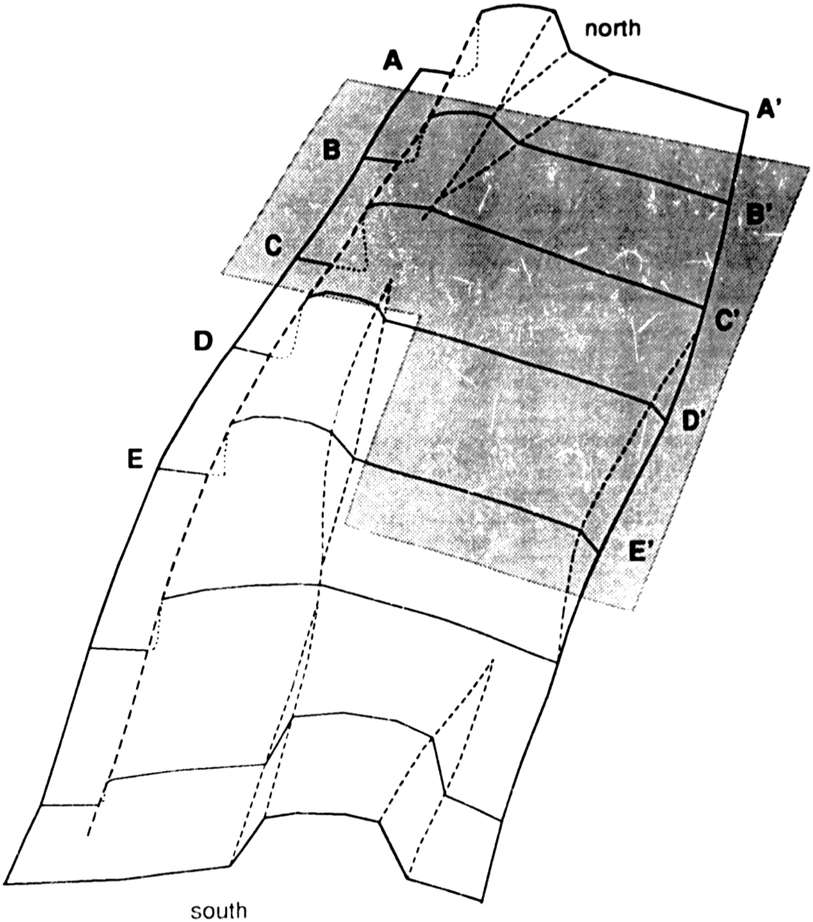


Figure 16: Schematic diagram of the southern Kotaneelee Anticline, showing an en-echelon step to the southeast and a culmination expressed in the east limb over exploration licence # 379 (shaded area). Cross-sections A-A' to E-E' are those of Figure 4. The southernmost 3 cross-sections are schematic only, based on observation and very few measurements.

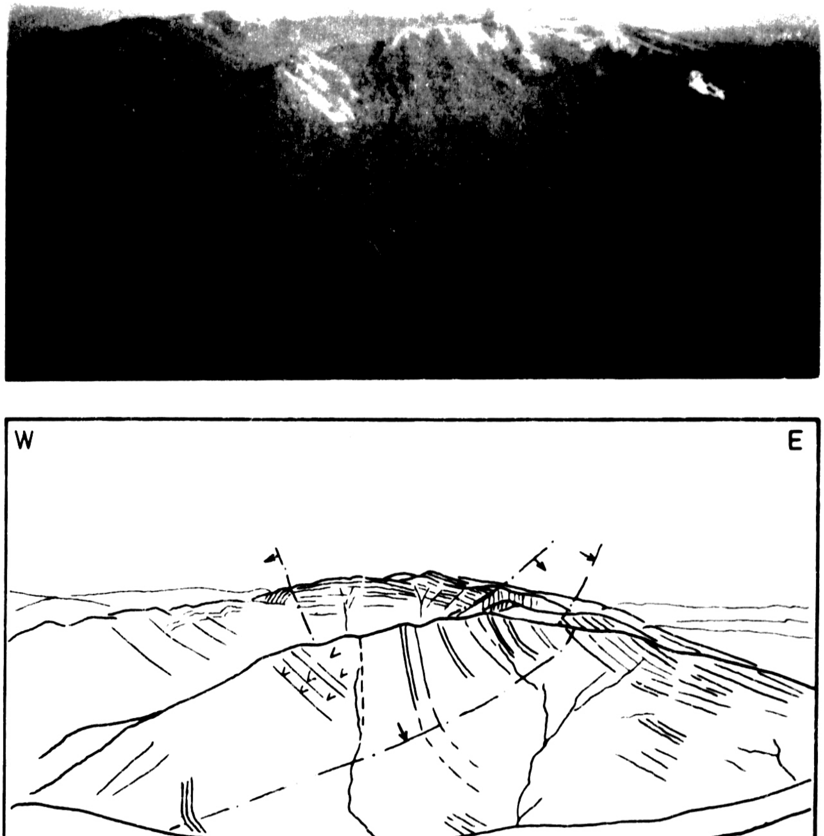


Figure 17: View to the north, onto the Kotaneelee Anticline, north of Kotaneelee Gap, illustrating the steepening of the east limb and the overall box fold geometry.

Figure 18: Near-vertical beds of the upper Mattson Formation in the west limb of the Kotaneelee Anticline; Kotaneelee Gap. (Stn. 19 b, UTM 432335/6717490).

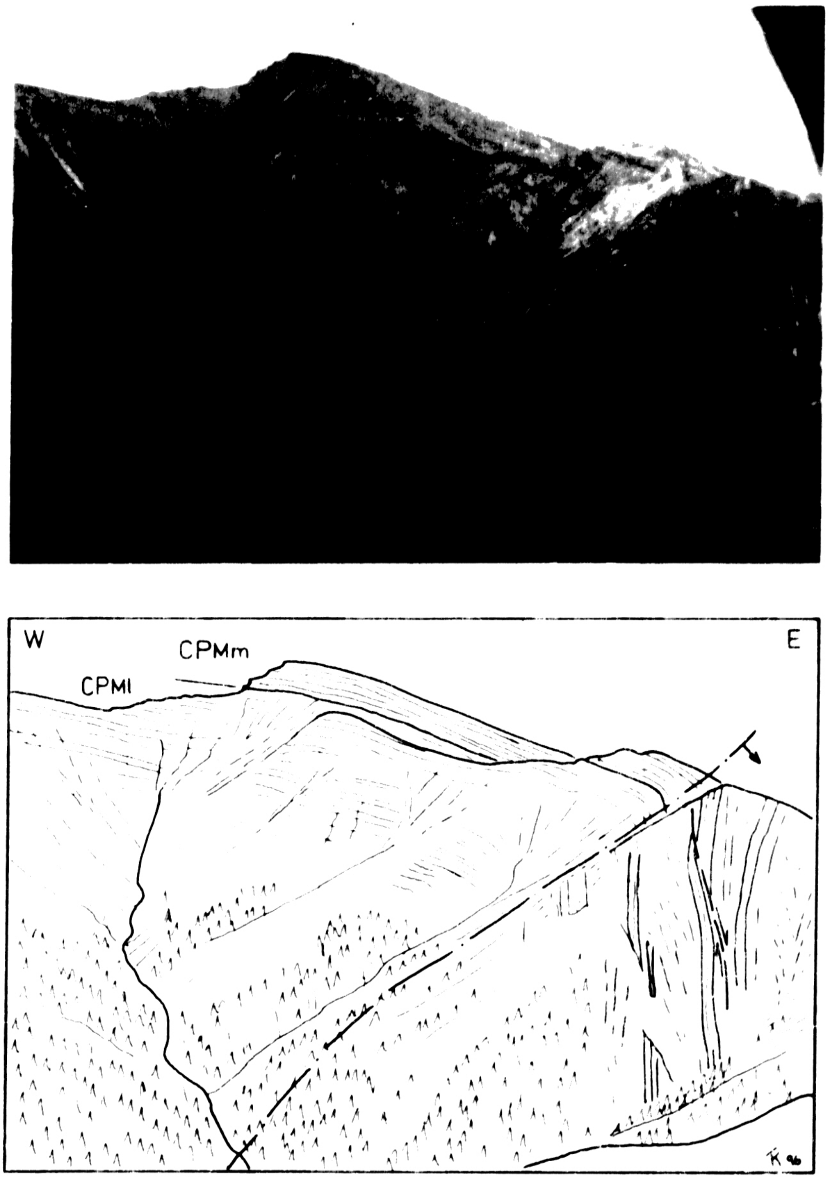
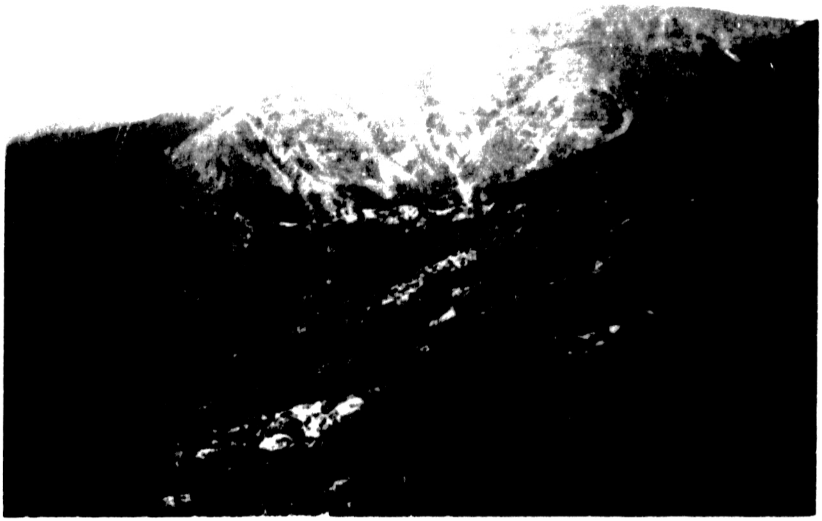


Figure 19. Monoclinal bend between the flat top of the Kotaneelee Anticline and the steep portion of the east limb, north of Kotaneelee Gap. View to the north.



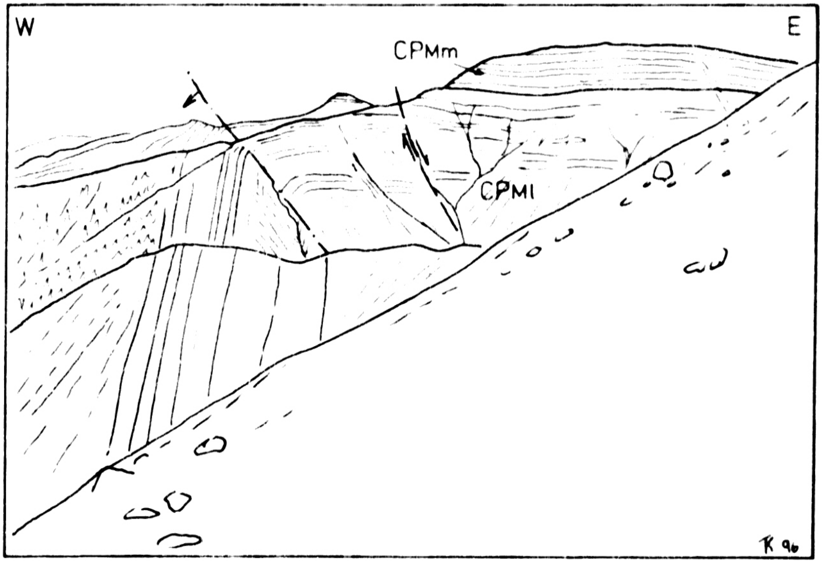


Figure 20: Monoclinal bend between the flat top and the steep west limb of the Kotaneelee Anticline, north of Kotaneelee Gap. View to the north.

Figure 21: The shallowly dipping (~ 18°) east limb of the Kotaneelee Anticline in the central portion of exploration licence # 379. View to the south.

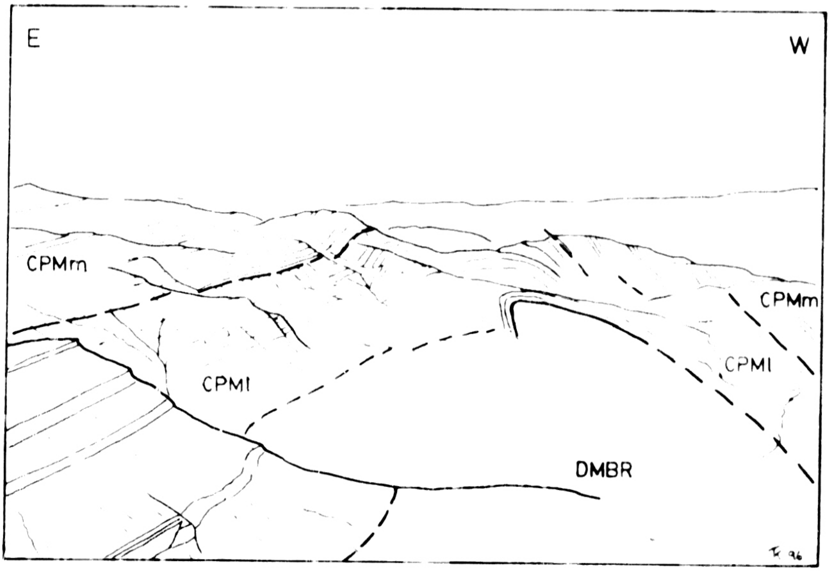


Figure 22: Box fold geometry of the Kotaneelee Anticline in the southern part of exploration licence # 379. Note steepening dips in the east limb and east vergence of the fold core. View to the south. See Figure 2 for legend.

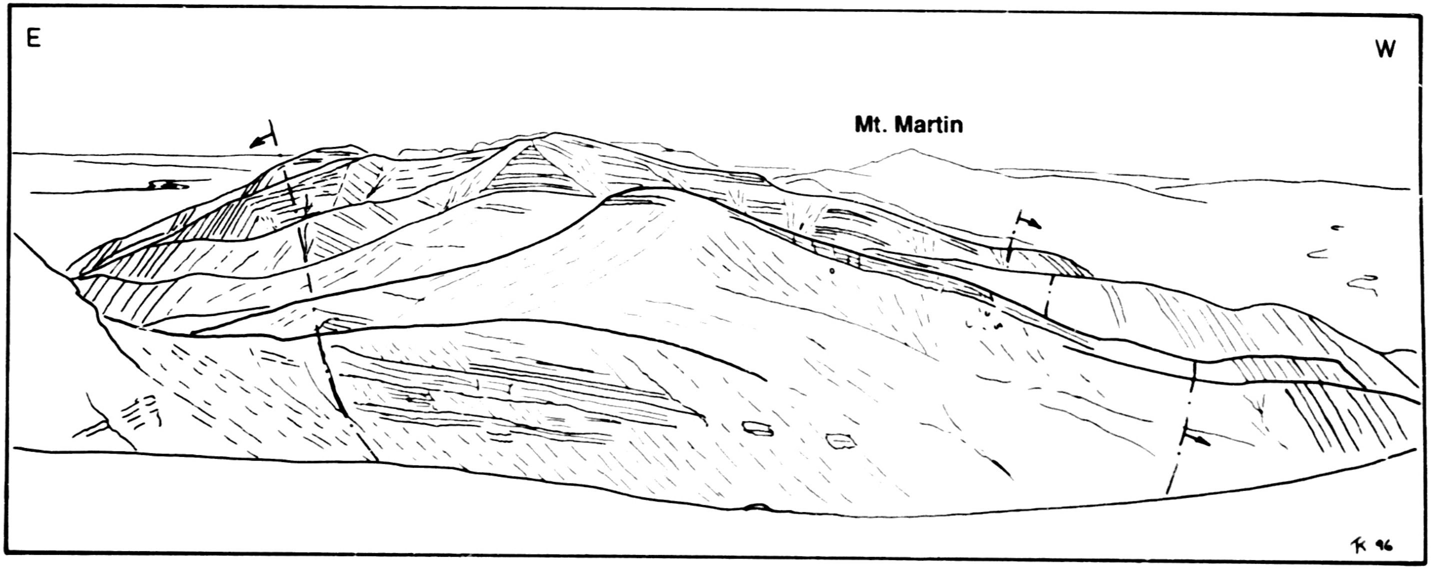


Figure 23: View to the south, showing the geometry of the southern part of the Kotaneelee Anticline, south of an en-echelon step to the southeast.

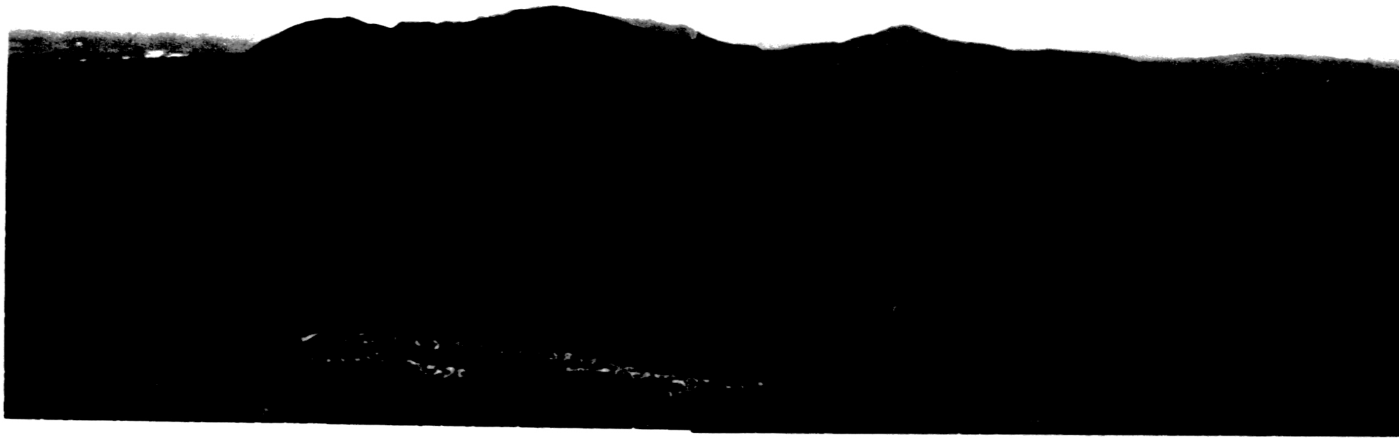


Figure 23 (continued)

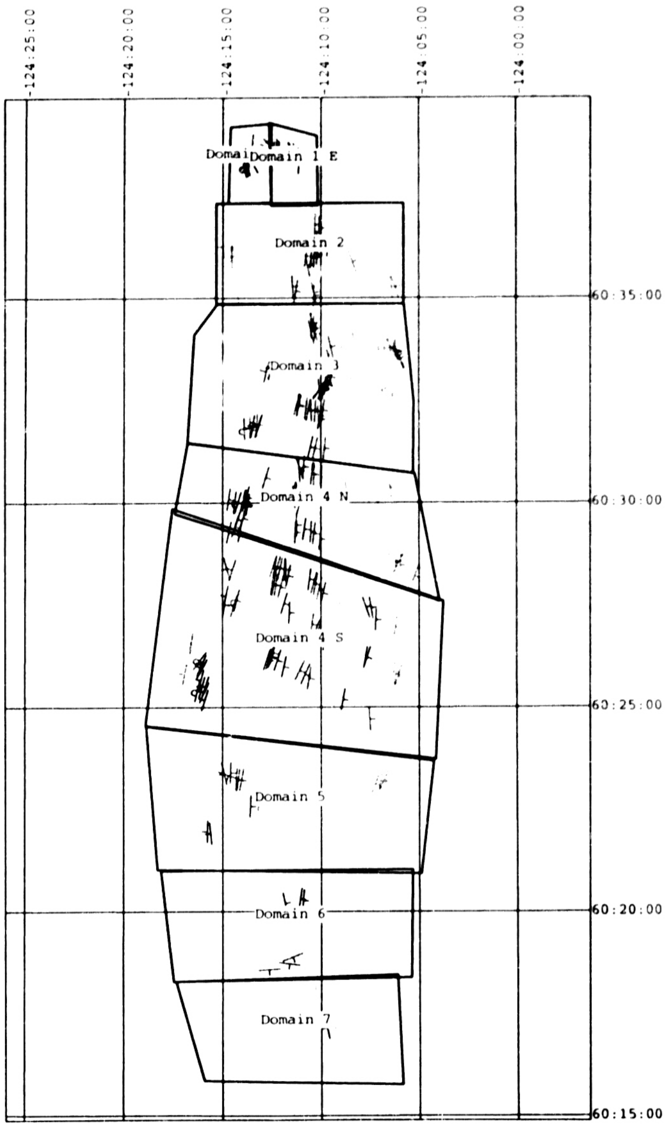


Figure 24: Structural domain map.

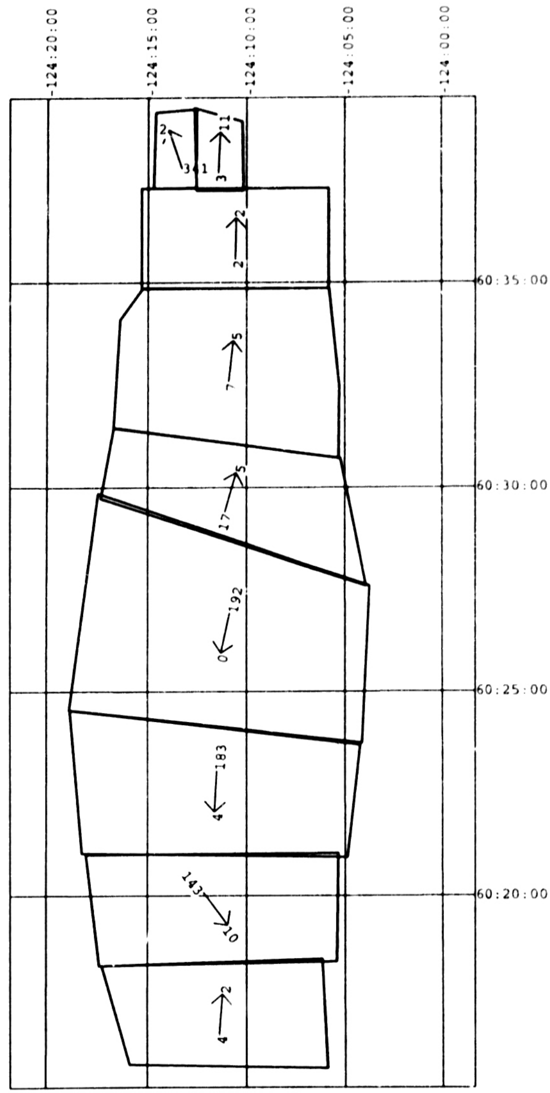


Figure 25: Structural domain map showing best fit cylindrical fold axes for each domain.

Figure 26: Monoclinal hinge between the near-vertical west limb of the Kotaneelee Anticline and the La Biche Syncline, as seen in siltstones underlying cherts of the Fantasque Formation. View to the south. (Stn. 19 a, UTM 431950/6718690).

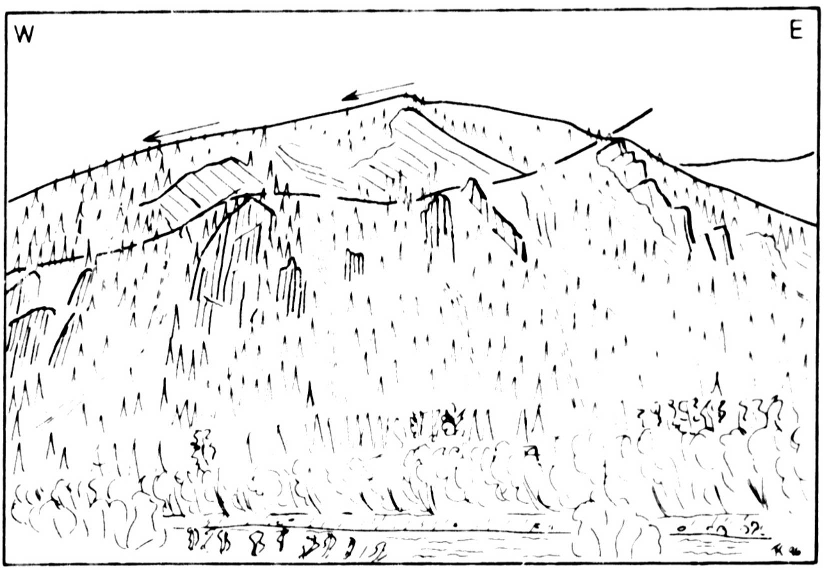


Figure 27: Large scale slumping in the near-vertical west limb of the Kotaneelee Anticline at Kotaneelee Gap. View to the north.

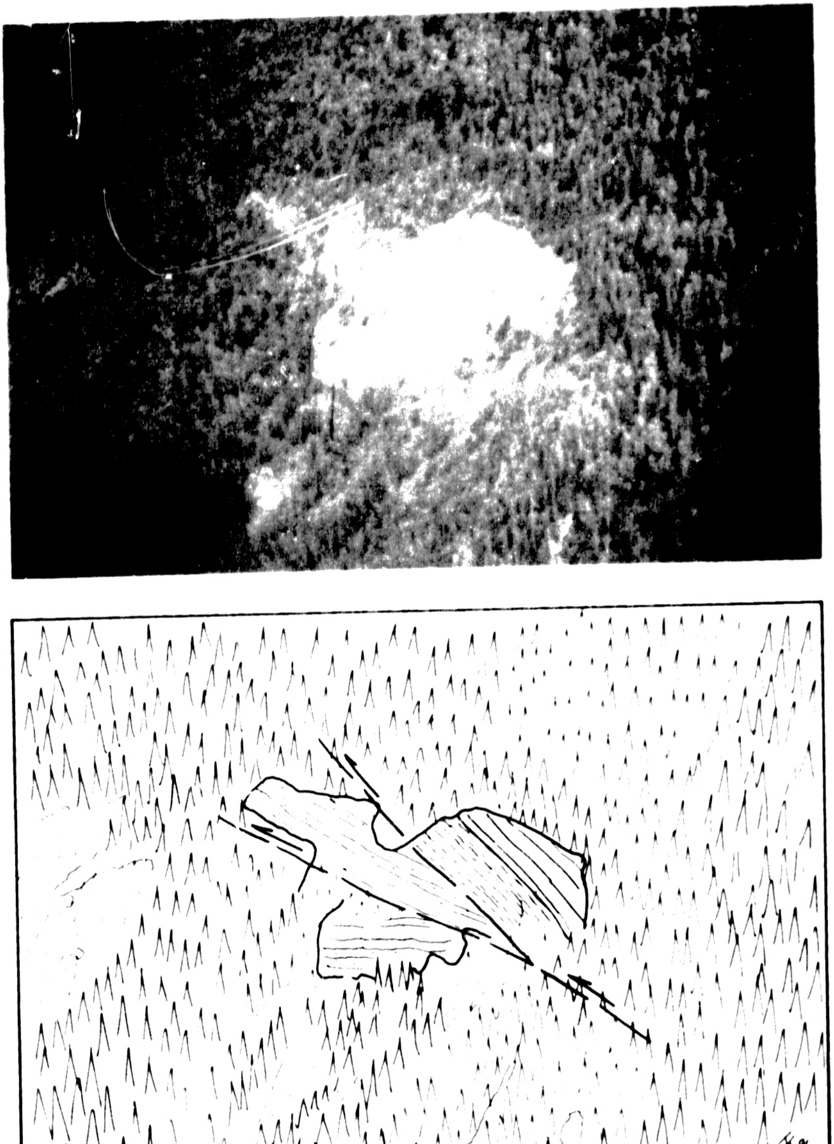


Figure 28: West-directed thrust fault with footwall splay, exposed in a slump block in the east limb of the Kotaneelee Anticline at Kotaneelee Gap. View to the north.

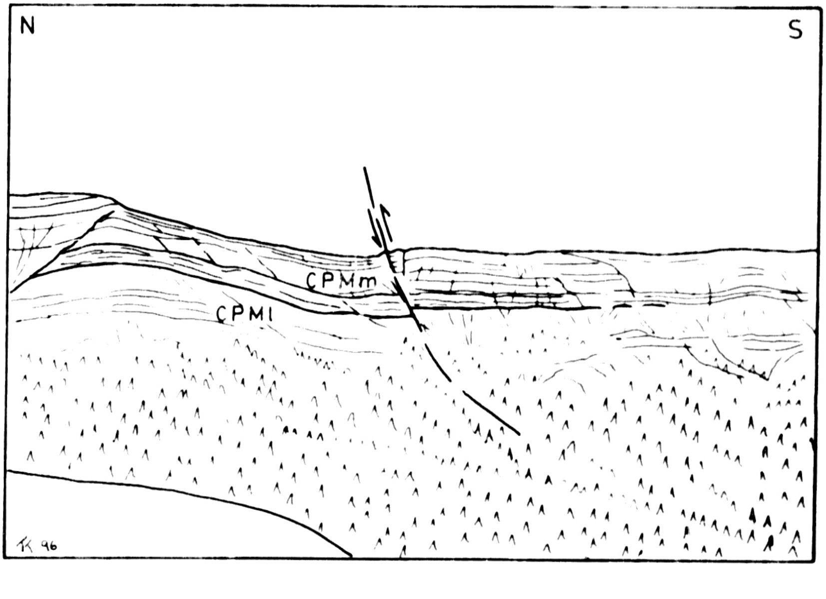


Figure 29: Transverse fault, offsetting the lower to middle Mattson contact vertically by ~ 40 m. View to the east. (Stn. 15, UTM 434640/6707750).

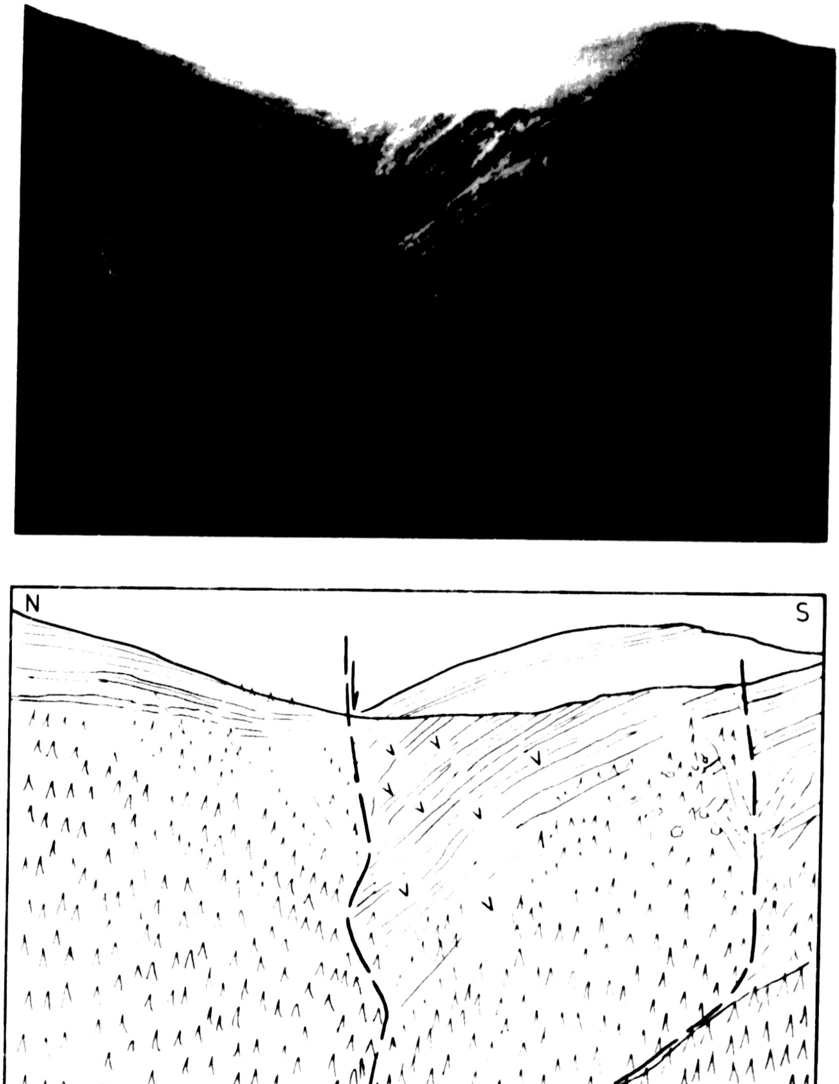


Figure 30: Rotation of middle Mattson strata by slumping between two transverse faults. View to the east. (UTM 436500/6713800).

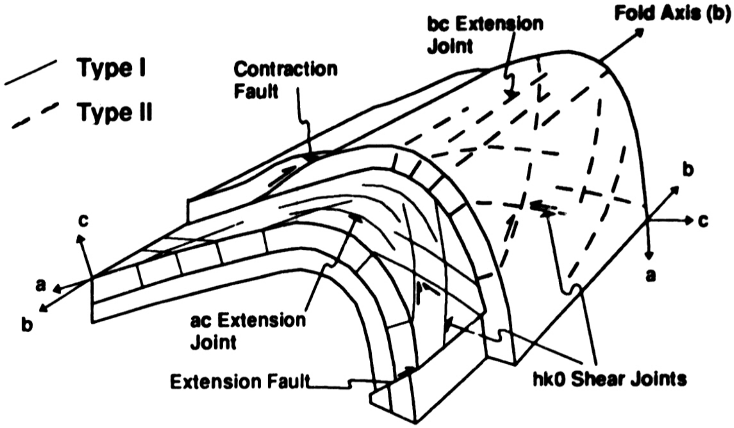


Figure 31: Fracture types and their orientations relative to a fold. After Price (1967), Stearns (1968) and Hancock (1985).

Figure 32: Prominent *ac* fractures (parallel to view direction) and subordinate *bc* fractures in siltstones underlying the Fantasque cherts.

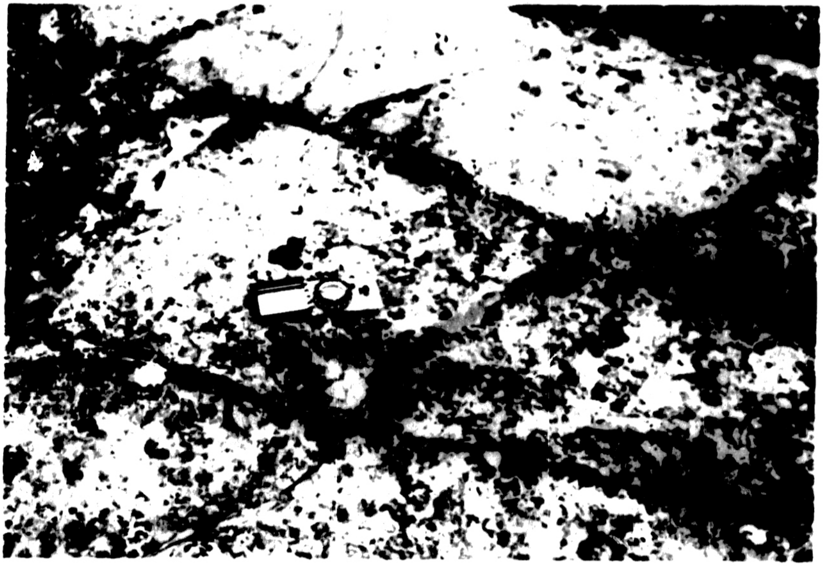


Figure 33: Oblique *hk0* fractures in sandstones of the middle Mattson Formation, possibly forming a Type II conjugate shear set. Compass (15 cm) is oriented parallel to north.

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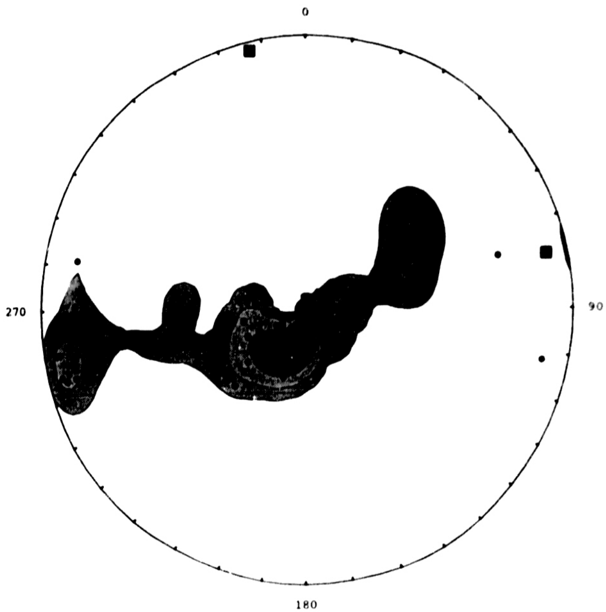
Appendix I

Lower Hemisphere, Equal Area Projections of Poles to Bedding



Title : Domain 1, combined
Drawing : PI Diagram
User : Tomas Kubli
Date : Aug 19/96 16:19
Project : Norcen Kotaneelee
-- Technical Data --

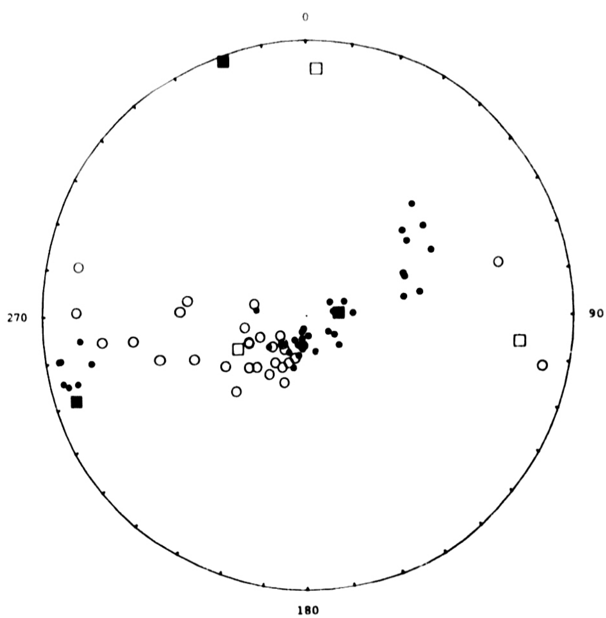
Projection : Schmidt
-- bedding --
Readings : 66
Distribution : Girdle
E3 Std. Scat. Angle: 9.2

EVector		EVal
234.2	80.2	0.71687
77.5	9.0	0.25750
346.9	3.8	0.02563

Contour Method : Probability
Concentration (k) : 100
Contours at : 2 5 10

-- Comments --

Company : Gaia Software Inc
Program : GaiaBASE 1.0A



Title : Domain1
Drawing : PI Diagram
User : Tomas Kubli
Date : Aug 19/96 16:14
Project : Norcen Kotaneelee
-- Technical Data --

Projection : Schmidt
-- bedding E limb --
Readings : 30
Distribution : Girdle
E3 Std. Scat. Angle: 7.2

EVector		EVal
245.8	66.0	0.81431
96.8	20.9	0.16994
2.5	11.3	0.01575

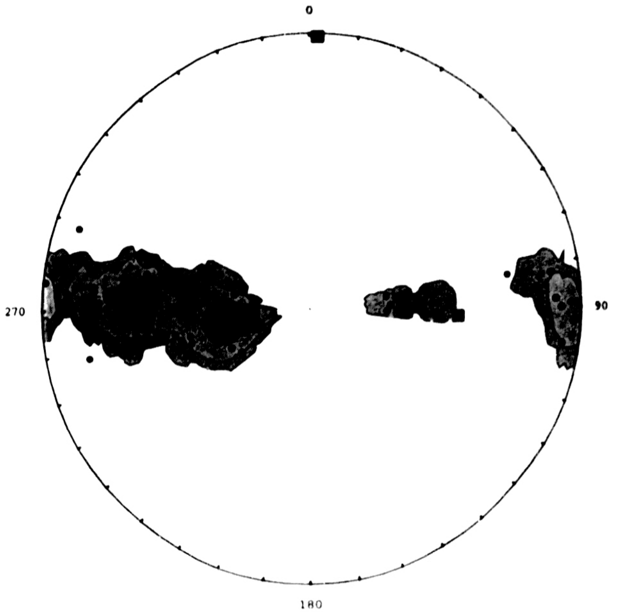
-- bedding W limb --
Readings : 38
Distribution : Girdle
E3 Std. Scat. Angle: 7.3

EVector		EVal
85.0	80.4	0.60818
250.4	9.3	0.24425
340.8	2.4	0.01599

-- Comments --

East limb - empty symbols
West limb - filled symbols
Poles to bedding - circles
Eigenvectors - squares

Company : Gaia Software Inc
Program : GaiaBASE 1.0A



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Drawing : PI Diagram
User : Tomas Kubli
Date : Aug 19/96 16:20
Project : Norcen Kotaneelee
-- Technical Data --

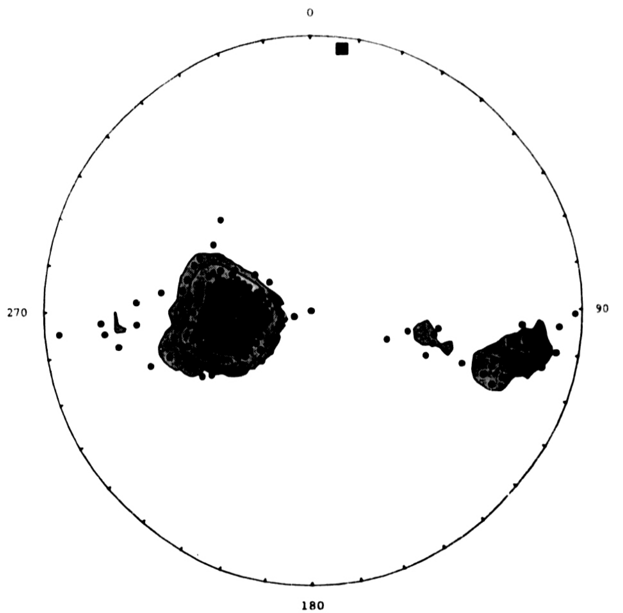
Projection : Schmidt
-- bedding --
Readings : 75
Distribution : Girdle
E3 Std. Scat. Angle : 5.8

EVector		EVal
270.0	46.4	0.75422
93.0	43.5	0.23558
1.6	1.5	0.01021

Contour Method : Counting Circle
Circle Size : 1
Contours at : 2 5 10

-- Comments --

Company : Gaia Software Inc
Program : GaiaBASE 1.0A



Title : Domain 3
Drawing : PI Diagram
User : Tomas Kubli
Date : Aug 19/96 16:21
Project : Norcen Kotaneelee
-- Technical Data --

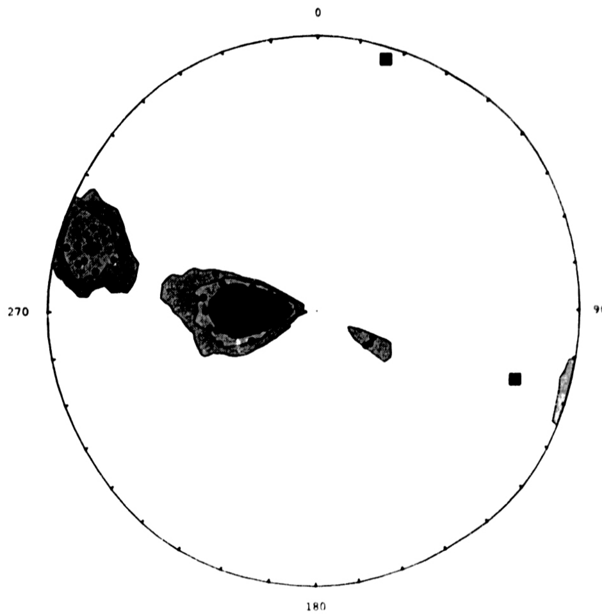
Projection : Schmidt
-- bedding --
Readings : 192
Distribution : Girdle
E3 Std. Scat. Angle : 6.0

EVector		EVal
266.3	65.2	0.68843
98.7	24.3	0.10284
6.6	4.7	0.01081

Contour Method : Counting Circle
Circle Size : 1
Contours at : 2 5 10

-- Comments --

Company : Gaia Software Inc
Program : GaiaBASE 1.0A



Title : Domain 4 N
Drawing : PI Diagram
User : Tomas Kubli
Date : Aug 19/96 14:47
Project : Norcen Kotaneelee

-- Technical Data --

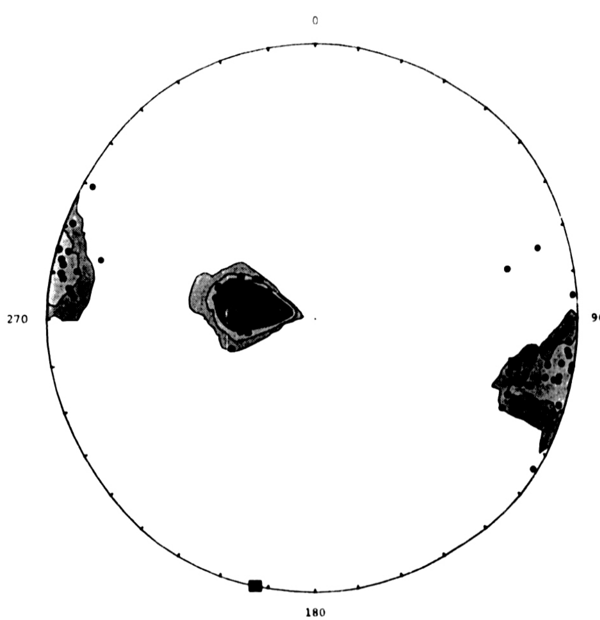
Projection : Schmidt
-- bedding --
Readings : 99
Distribution : Girdle
E3 Std. Scat. Angle: 3.7
EVector EVal

275.0	66.4	0.86200
108.7	23.0	0.13387
16.6	5.0	0.00414

Contour Method : Counting Circle
Circle Size : 1
Contours at : 2 5 10

-- Comments --

Company : Gaia Software Inc
Program : GaiaBASE 1.0A



Title : Domain 4 S
Drawing : PI Diagram
User : Tomas Kubli
Date : Aug 19/96 16:22
Project : Norcen Kotaneelee

-- Technical Data --

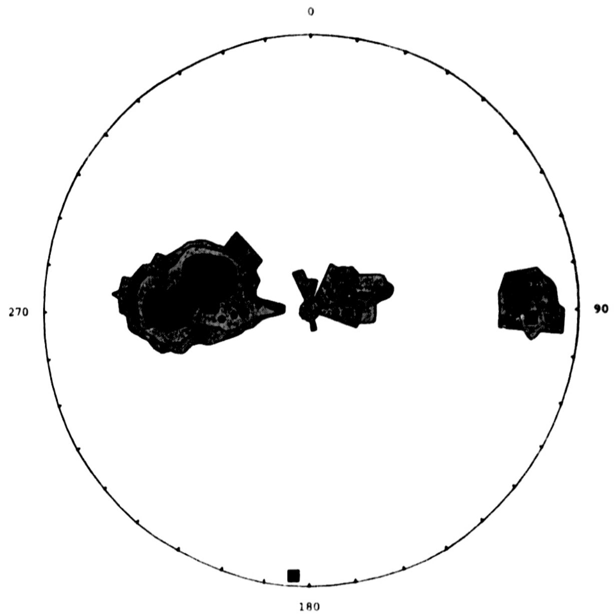
Projection : Schmidt
-- bedding --
Readings : 144
Distribution : Girdle
E3 Std. Scat. Angle: 5.5
EVector EVal

282.7	65.2	0.75267
102.5	24.8	0.23819
192.5	0.1	0.00914

Contour Method : Counting Circle
Circle Size : 1
Contours at : 2 5 10

-- Comments --

Company : Gaia Software Inc
Program : GaiaBASE 1.0A



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Drawing	PI Diagram
User	Tomas Kubli
Date	Aug 19/96 16:23
Project	Norcen Kotaneelee

-- Technical Data --

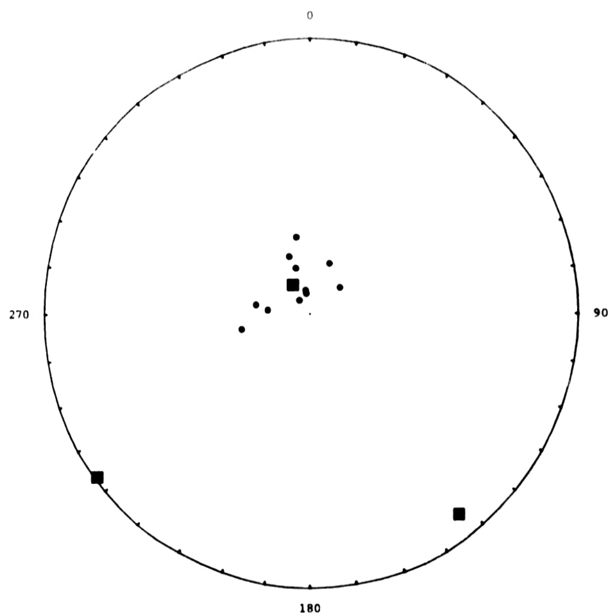
Projection : Schmidt
-- bedding --
Readings : 47
Distribution : Girdle
E3 Std. Scat. Angle : 4.8

EVector		EVal
285.4	70.9	0.79091
92.1	18.7	0.15940
183.4	4.1	0.00713

Contour Method : Counting Circle
Circle Size : 1
Contours at : 2 5 10

-- Comments --

Company : Gaia Software Inc
Program : GaiaBASE 1.0A



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Drawing	PI Diagram
User	Tomas Kubli
Date	Aug 19/96 16:23
Project	Norcen Kotaneelee

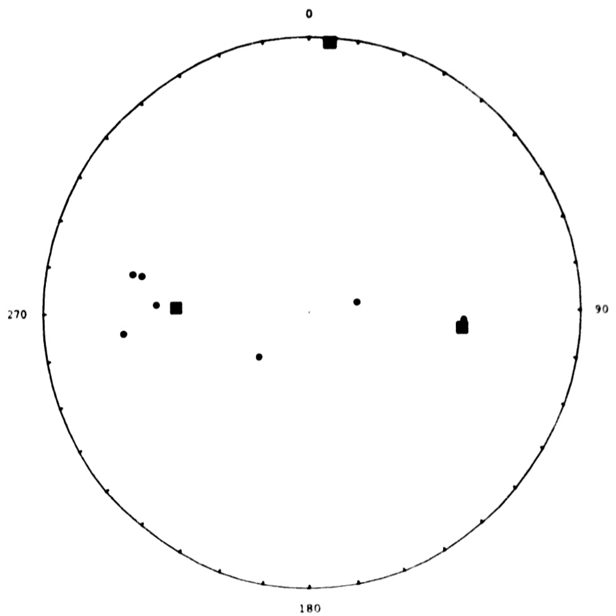
-- Technical Data --

Projection : Schmidt
-- bedding --
Readings : 11
Distribution : Cluster
E1 Std. Scat. Angle : 11.4

EVector		EVal
329.3	80.2	0.96086
233.4	1.0	0.03015
143.2	9.8	0.00899

-- Comments --

Company : Gaia Software Inc
Program : GaiaBASE 1.0A



Title : Domain 7
Drawing : PI Diagram
User : Tomas Kubli
Date : Aug 19/96 16:24
Project : Norcen Kotaneelee

-- Technical Data --

Projection : Schmidt
-- bedding --
Readings : 7
Distribution : Girdle
E3 Std. Scat. Angle: 7.2

EVector		EVal
272.2	47.6	0.68390
96.0	42.4	0.30049
4.3	1.9	0.01561

-- Comments --

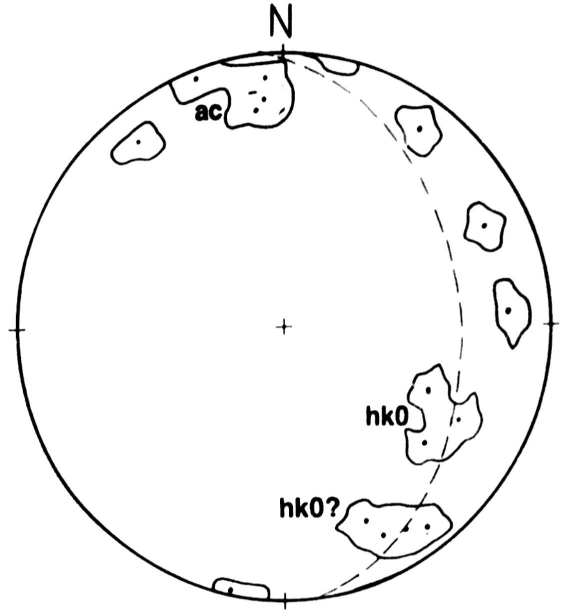
Company : Gaia Software Inc
Program : GaiaBASE 1.0A

Appendix II

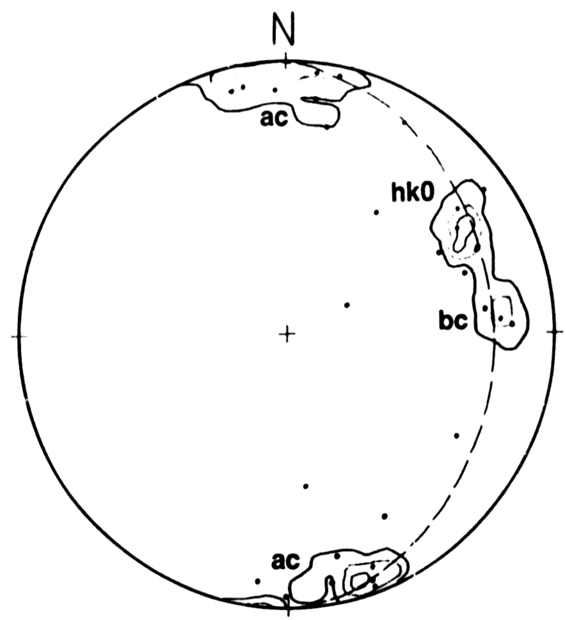
Lower Hemisphere, Equal Area Projections of Poles to Fractrures

Note: dashed great circles represent mean bedding planes.

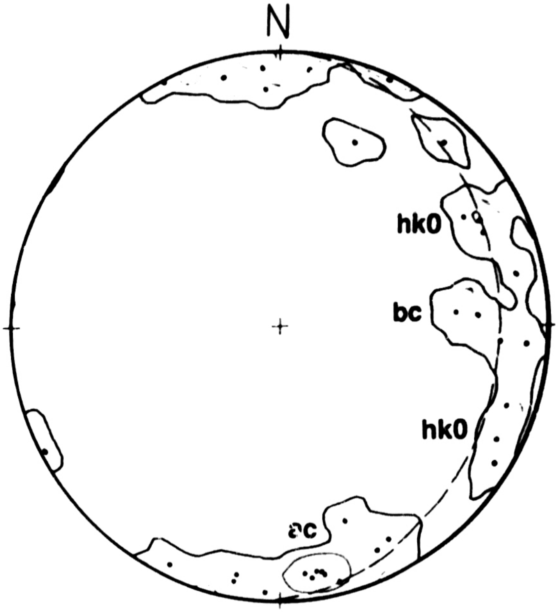
Poles to fractures
Domains 1 and 2, east limb
N=16, countours at 5, 10



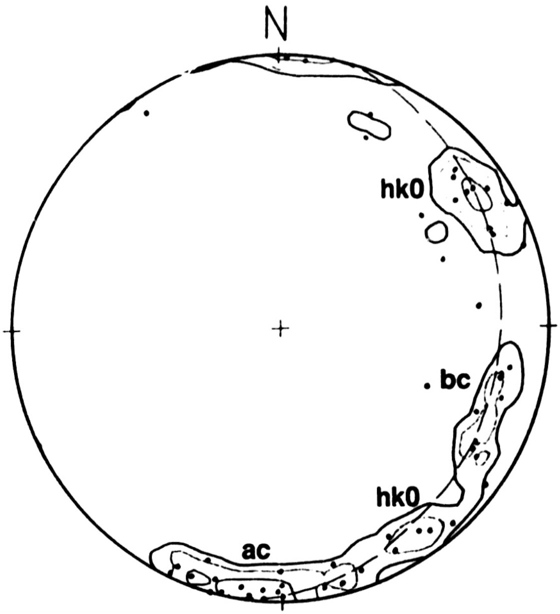
Poles to fractures
Domain 3, east limb
N=30, countours at 4, 8, 12



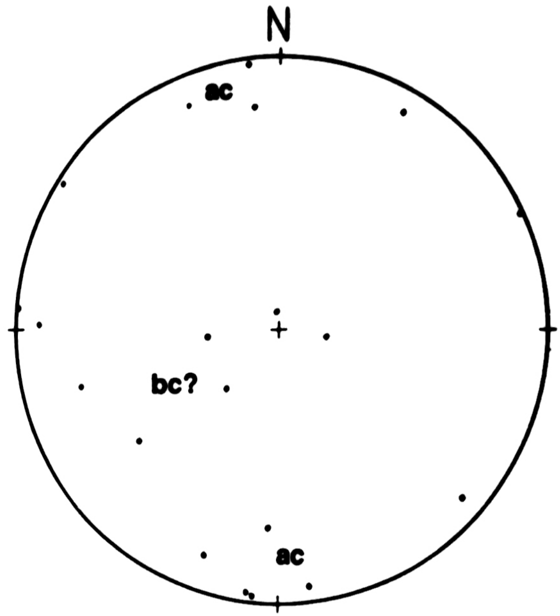
Poles to fractures
Domain 4 north, east limb
N=33, contours at 2, 5, 10



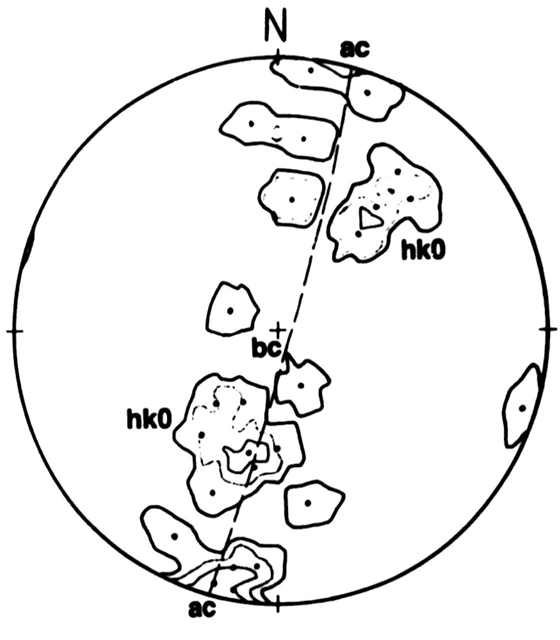
Poles to fractures
Domain 4 south, east limb
N=52, countours at 3, 6, 12



Poles to fractures
Domains 1, 2 and 3, west limb
N=21



Poles to fractures
Domains 4 north & south, west limb
N=29, countours at 2, 5, 10



Supplement I

Digital files:

Name:	Format:	Description:
TEKFIELD.XLS	Microsoft Excel® file	Raw outcrop data file
KOT.DBS	Tripod® ascii file	Structural data in Tripod format
KOTPROJ.ZIP	Zipped Gaiabase® file	Kotaneelee project in Gaiabase format