Strain analysis in the Bullbreen Group (early Silurian), central western Spitsbergen, using antitaxial extension veins.

Matthew Edward. Dodt
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STRAIN ANALYSIS IN THE BULLBREEN GROUP (EARLY SILURIAN),
CENTRAL WESTERN SPITSBERGEN,
USING ANTITAXIAL EXTENSION VEINS

by

Matthew Edward Dodt

A Thesis
submitted to the Faculty of Graduate Studies
through the Department of
Geology in Partial Fulfillment
of the requirements for the Degree
of Master of Science at
The University of Windsor

Windsor, Ontario, Canada
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ABSTRACT

STRAIN ANALYSIS IN THE BULLBREEN GROUP (EARLY SILURIAN),
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Pre-Carboniferous rocks of the St. Jonsfjorden area, western Spitsbergen have been subjected to three major deformational phases. The second of these has produced calcite-filled extension fractures within the younger of two rock packages. The fracture fillings are optically continuous fibrous crystals which frequently have a sigmoidal form. The differences in orientation of individual fibers can be related to changes in the orientation of incremental strains relative to the fracture during progressive deformation. The fiber length in a given orientation is proportional to the amount of incremental extension in that direction. Incremental strains recorded by these fibers indicate that dextral rotation of the rocks has taken place in a plane currently dipping to the southwest. All fibers reflect initiation, using present-day coordinates, in a west-southwest direction with the first-formed fiber components subsequently rotated into parallelism with local fold axes. The extension directions and rotation are explained by a modified model of transpression which incorporates transverse and thrust shear components.
To Pamela
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CHAPTER ONE
INTRODUCTION

The Svalbard archipelago, a group of six large and several smaller islands, is located north of the Scandinavian Peninsula, on the northwestern corner of the Barents Shelf (Fig. 1). The largest of the islands, Spitsbergen, contains rock sequences believed to form a northern extension of the Caledonian fold belt (Harland et al., 1979). Rocks affected by the Caledonian Orogeny outcrop in west and north-central Spitsbergen, Nordaustlandet, and several smaller islands (Fig. 2). These variably metamorphosed rocks, ranging in age from Precambrian through Middle Ordovician, are known as the Hecla Hoek Succession (Birkenmajer, 1981, p.269).

Spitsbergen's position at the northwestern margin of the Eurasian plate and extensive geologic record showing numerous episodes of deformation have been used to develop and interpret cross-continental correlations. This observation is supported by a reconstruction of the circum-Atlantic Caledonian mountain system during Late Cretaceous time, shown in Figure 3 (Birkenmajer, 1981, p. 265).

Pre-Carboniferous Spitsbergen has been divided into three major geologic provinces (Fig. 4, B) on the basis of biostratigraphy and structure. Rocks of the Western Province exhibit strong lithologic associations with the
Figure 1. Location map of Svalbard (after Birkenmajer, 1981, p. 266).
PKF - Prins Karls Forland
OIIL - Oscar II Land

Figure 2. The Islands of Svalbard showing the major exposures of the Caledonian fold belt (cross-hatched). The study area, located on the west coast of Spitsbergen, is shown in Figure (after Birkenmajer, 1981, p. 268).
Figure 3. Reconstruction map of the circum-Atlantic Caledonian mountain system (shaded area) prior to continental drift in late Cretaceous time (after Birkenmajer, 1981, p. 269).
North Greenland fold belt. Rocks of the Eastern and Central Provinces are similar to those found in northern Norway. It has been inferred that horizontal strike-slip movements along ancient fault zones (Fig. 4, A) have placed these two regions of contrasting strata adjacent to each other, giving Spitsbergen its present configuration (Harland and Wright, 1979).

Central western Spitsbergen has been further divided into two areas: Prins Karls Forland and Oscar II Land (Fig. 2). The pre-Carboniferous rocks of these regions are referred to as the Forland and Western Complexes, respectively (Manby, 1978). The field work for this project was conducted in the St. Jonsfjorden area of Oscar II Land, on the west coast of Spitsbergen opposite Prins Karls Forland (see Fig. 5). The rock succession of the St. Jonsfjorden area consists of two major rock packages; the lower unit showing characteristics of a tectonically stable sedimentary environment and the upper displaying molasse affinities (Morris et al., 1983). The upper unit is referred to here as the Bullbreen Group following the nomenclature of Harland et al. (1979). The Bullbreen Group, of early Silurian age (Scrutton et al., 1976), incorporates the youngest rocks of the Western Complex.

This study has been undertaken to define part of the deformational history of the Bullbreen Group. This was achieved by (1) determining, through the use of structural fabrics and fibrous crystals in extension veins, the
Figure 4. Sketch maps of the pre-Carboniferous geologic provinces of Svalbard. A. Sketch showing the inferred late Devonian transcurrent movements that juxtaposed the three provinces. The drawing is not to scale and the locations of the provinces are approximate. B. Outline map showing the present configuration and the inferred boundary fault zones of Svalbard (after Harland and Wright, 1979).
Figure 5. Map showing the localities of the St. Jønsfjorden field area.
variation in extension direction recorded in sediments of the upper rock package and (2) calculating relative values for finite, incremental, and cumulative strains recorded by these carbonate extension veins. The integrated data are used to define more precisely the strain history of the Bullbreen Group during vein formation and help evaluate recent theories on the origin of tectonic structures in the unit.
CHAPTER TWO
GEOLOGY OF ST. JONSFJORDEN

2.1 Geography and Field Conditions

The islands of Svalbard, Land of Frozen Shores, are under Norwegian sovereignty. They are located 950 km from the northern coast of Scandinavia and extend to within 1,046 km of the North Pole (Young, 1978). Most of the 62,000 square kilometres of land surface is covered by glaciers or frozen as permafrost. Access to the area is limited; the jagged topography isolates inhabited areas, roads do not extend beyond the towns, and pack ice surrounds Svalbard eight months of the year. Ships and helicopters offer the only means of transportation during the seasonal summer thaw, because the ground surface consists of crevassed glaciers and soft, swampy tundra.

In the field area, the topography of St. Jonsfjorden is rugged, with mountain peaks rising 600 to 700 metres above sea level adjacent to active glaciers (Figs. 6, 7 and 8). Meltwater streams, flowing adjacent to and over ice, rework moraines around glacier margins and sort the debris as it is transported to the fjord. The calving of glaciers occurs all summer when the fjord is free of pack ice. Scattered rock exposures are found throughout the study area shown in Figure 5. Talus covers many ice-free slopes, making access to outcrops somewhat difficult.

The field work for this study was performed during July
Figure 6. Photograph and sketch of the central southeastern St. Jonsfjorden area. The view, from the top of central Ankerfjella, is toward the southeast.
Figure 7. Photograph and sketch of the central southwestern St. Jonsfjorden area. The view, from the top of western Ankerfjella, is toward the south.
Figure 8. Photograph of northwestern Holmesletfjella and the front margin of Bullbreen Glacier. The view, from the top of eastern Bulltinden, is toward the east.
and August, 1983, as part of the research undertaken by Dr. Alan Morris, coordinator of the Wayne State University Spitsbergen Expedition. The summer base camp for the expedition was at Gjertsenodden, on the north shore of St. Jonsfjorden. Access to the field area, which was located on both sides of the fjord, was made possible with a Zodiac inflatable water-craft, equipped with a 25-horsepower motor. Field relationships were mapped at a 1:10000 scale across an area of approximately 35 square kilometres extending over both sides of St. Jonsfjorden. The information obtained was used to update a previous map made by earlier expedition members. This strain analysis was expanded into a joint project between the University of Texas at San Antonio and the University of Windsor. The present study was completed at the University of Windsor under the direction of Dr. Paul Holm.

2.2 Stratigraphy of St. Jonsfjorden

The geologic and structural aspects of St. Jonsfjorden as they relate to west Spitsbergen have been investigated by Weiss (1953), Hjelle et al. (1979), Harland et al. (1979), and Morris et al. (1983). In these reports, workers have included reconnaissance maps of the Western Complex with their explanations of the regional geology. An updated, generalized geologic map of the St. Jonsfjorden area, at a 1:200000 scale, is presented in Figure 9. This map, showing the extent of the units comprising the lower and upper rock
Figure 9. Generalized geologic map of the St. Jonsfjorden area.
packages, as well as the Permo-Carboniferous rocks of the field area, has been compiled from the work of A. Morris, L. Kanat, J. Ague, S. Grön, R. Ratliff, and the author during the 1982-1983 field seasons. Most of the geologic contacts shown between lower package map units are tectonic, i.e. these lithologies are separated from each other by low-angle to moderate westward-dipping faults (Hjelle et al., 1979). Only the St. Jonsfjorden and Comfortlessbreen groups show evidence of having once formed a continuous sequence (Morris, personal communication, 1984). The basal contact of the Bullbreen Group is also defined by a thrust zone: Bullbreen lithologies are found juxtaposed against all members of the lower rock package. Lithologic and structural differences, such as the orientations of cleavage, fold axes, and lineations, help to define the boundaries between the two rock packages.

2.2.1 Lower Rock Package

The lower rock package, Late Precambrian to (?)Cambrian in age, consists mainly of miogeoclinal sedimentary and volcanic rocks (Harland et al., 1979). Although the metamorphic grades of these rocks have been used to infer stratigraphic relationships within the older rock package, no definitive chronological succession has been established for these lower rock units. The following geological descriptions for the lower package are compiled from field notes, supplemented in part from Waddams (1983) and
Horsfield (1972). The order in which they are discussed does not imply a stratigraphic order.

Rocks with the highest metamorphic grade in the field area, eclogite-blueschist facies, are those of the Vestgötabreen Complex. This unit consists of a sequence of quartz-mica mylonites, greenstones, and glaucophane schists with occasional pyroxene pods and serpentinites (Ohta, 1979). They are restricted to the area south and east of Holmesletfjella.

Exposed along Forlandsundet are the garnet-biotite schists of the Müllerneset Formation (Ague and Morris, 1985). The dominant lithologies of this group are pelites and psammites which contain minor thicknesses of carbonate.

The lower package also contains tillites of the Comfortlessbreen Group. Although the metamorphic grade of this set of rocks has not been established, tillites found to the north of St. Jonsfjorden and on Prins Karls Forland are biotite-grade. Similarities between carbonate clasts found throughout this group have resulted in its use as a major stratigraphic correlation horizon across Spitsbergen and the Arctic (Hambray, 1983). Another distinct, mappable unit is the chlorite-grade St. Jonsfjorden Group, consisting of psammo-pelites, banded limestones, breccias, and meta-volcanics. This unit can be found on both sides of St. Jonsfjorden.

Lithologies of the lower package, which are similar to highly deformed, metamorphosed sequences found throughout
West Spitsbergen, have a more extensive outcrop area around St. Jonsfjorden than the Bullbreen Group. It has been suggested that these lower package rocks were deposited in an aulacogen prior to the Caledonian Orogeny (Ague and Morris, 1985). A failed rift zone can provide a deep depositional basin in which great thicknesses of strata can accumulate; the lower package has been estimated to be 18-20 km thick (Harland et al., 1979). Also, elevated geothermal gradients in a rift are responsible for early metamorphism of the rocks. The trend of the Spitsbergen Caledonides is oriented at a high angle to the main Caledonide trend (see Fig. 3). This angular relationship has been used to support the idea that the depositional basin for the older rock package is the failed arm of a triple-point junction (Ague and Morris, 1985).

It has been suggested that the major metamorphism (Fig. 10) of the Forland and Western Complexes occurred as a single thermal event which began prior to and continued throughout the first deformational event (Manby, 1978; Ague and Morris, 1985). As a result of the great thickness of this lower rock package, stratigraphically older rocks were assumed to be more deeply buried and thus record higher metamorphic grades.

The mineral assemblages in the Vestgøtabreen Complex are indicative of a compressive continental margin. The possibility of subduction processes operating during part of this first deformational event, attributed to the
Figure 10. Map of central-western Spitsbergen showing the distribution of metamorphic facies within the pre-Carboniferous rocks of Prins Karls Forland (the Forland Complex) and Oscar II Land (the Western Complex) (after Ague and Morris, 1985).
development of the Vestgötabreen Complex, has been suggested (Kanat, personal communication).

2.2.2 Upper Rock Package – The Bullbreen Group

The upper rock package in the St. Jonsfjorden consists of approximately 500 metres of carbonates and calcareous clastic deposits. In contrast to the lower package, exposures of the Bullbreen rocks are restricted to the immediate area of St. Jonsfjorden. This group has been divided into two units by Harland et al. (1979); the Motalafjella and Holmesletfjella Formations. The former contains massive gray limestone and the latter consists of medium- to coarse-grained sandstone and conglomerate with interbedded siltstones and mudstones. Kanat (personal communication, 1984) has further distinguished the basal thrust contact zone of the Bullbreen Group as a distinct tectono-stratigraphic unit separate from the Motalafjella Formation. The descriptions that follow reflect the most recent interpretations of Bullbreen Group stratigraphy.

The basal unit of the Bullbreen Group has no primary bedding fabric and consists of an assembly of brecciated lithologies set in a dolomitic matrix. This carbonate matrix has experienced widespread recrystallization and silicification (Ratcliffe, 1985). This unit weathers to a distinct orange colour making it an easily recognized stratigraphic marker. The zone is seen in its greatest extent at southern Bulltinden, with lesser outcrops found at
Figure 11. Photograph of northern Holmesletfjella, showing a large exposure of the orange-coloured basal zone. The zone extends from the lower left corner to the center of the photograph. The view, from the top of eastern Holmesletfjella, is toward the west.
northern Holmesletfjella (Fig. 11) and near the base of Ankerfjella. Outcrops of this basal zone on the southern side of St. Jonsfjorden contain large clasts of limestone and dolomite, as well as greenstone, schist, and other metamorphic rocks (Kanat, personal communication, 1983). All of these metamorphic assemblages can be found in the Vestgøtabreen Complex. This zone is always found to be associated with the contact between the Bullbreen and lower rock package lithologies. Lower package rocks found below this zone contain distinct deformation patterns which differ from the relatively unmetamorphosed Bullbreen sediments. The lower contact of this unit most likely represents a décollement, along which displacement occurred. The assortment of jumbled clasts represents a tectonic melange over which the Bullbreen thrust sheets moved. The colour of this basal zone may be due to alteration by mineralized fluids moving along the thrust.

Overlying the basal zone is the Motalafjella Formation, consisting of gray, micritic limestone. This carbonate horizon reaches its greatest thickness, about 100 metres, in an overturned nappe on Motalafjella. The unit appears to thin towards the north and northeast, and becomes more crystalline and dolomitic toward its contact with the basal zone. Fossil assemblages of corals, trilobites, and crinoids found in this unit also occur in pebbles and boulders of this lithology found in the polymict conglomerates of the Holmesletfjella Formation. These
fossils indicate the age of this limestone to be Early Silurian, probably Ludlow to Wenlock (Scrutton et al., 1976). These fossils provide the only definitive age for the Bullbreen Group.

The Holmesletfjella Formation makes up a majority of the Bullbreen Group exposures. The thickness of this formation is estimated to be a minimum of 360 metres, as the upper contact of this group has been removed by erosion. Black slates at the base of the Holmesletfjella Formation are 20 to 25 metres thick and overlie the Motalafjella Formation. These micaceous slates occur to a limited extent on the south shore at Bulltinden and Holmesletfjella. Above this lower black slate, a calcareous mudstone unit with interbedded calcareous siltstone is exposed at northwest Holmesletfjella and on the south side of Ankerfjella. Bed thicknesses of both the mudstones and siltstones are variable and range from 0.01 to 0.2 metres. This unit contains the most extensive development of extension veins visible in the area. The veins occur principally in the mudstone units and areas with more mudstone have a greater number of veins.

Conformably overlying these mudstones and siltstones are the Holmesletfjella conglomerates. A massive horizon, termed the Bulltinden Conglomerate, occurs near the middle of the Holmesletfjella Formation and appears in its greatest extent at Bulltinden. A massive conglomerate is also found near the top of Ankerfjella. Unit thickness of the
conglomerates varies from 10 to 50 metres over a distance of several metres, and clasts up to 1.5 metres across can be found. The conglomerates have associated with them medium-to coarse-grained sandstones which are less than 1.0 metre thick. Most of the clasts in these conglomeratic horizons appear to be derived from the lower package lithologies. Boulders of gray limestone and brown dolomite are abundant with subordinate quartzite, black slate, garnet-mica schist, meta-diabase, skarn, and phyllite (Hjelle et al., 1979). Kanat (personal communication, 1983) has noted garnet-bearing clasts in the conglomerates at Motalafjella which may have been derived from the Vestgötabreen Complex.

A black, calcareous slate separates the conglomerates from an upper 60 to 100 metre thick siltstone and mudstone sequence. The lithologic characteristics of the upper mudstone and siltstone unit are similar to those of the lower mudstone and siltstone group. The extent of extension vein development in this upper mudstone-siltstone unit is unknown. The map distribution of this upper unit is inferred on the basis of a very limited number of exposures.

Based on the restricted occurrence and clast size of the Holmesletfjella conglomerates, it has been suggested (Hjelle et al., 1979) that the Bullbreen Group was deposited as an intermontane molasse during the Caledonian Orogeny. The distance over which the Bullbreen Group has been displaced along the relatively planar basal thrust surface is not known. The present outcrop pattern of the Bullbreen
Group forms a series of klippen, making the margins of the depositional basin difficult to determine (Harland, 1978).

2.2.3 Permo-Carboniferous Rocks

As indicated in Figure 9, younger rocks of Permo-Carboniferous age, thickly-bedded carbonates, sandstones and siltstones, are found in a narrow band on Thorkelsenfjella and to the east of St. Jonsfjorden. This group unconformably overlies the older rock units (Harland et al., 1979) and shows little to no metamorphism and no penetrative deformation fabrics.

2.3 Deformation History of St. Jonsfjorden

The pre-Carboniferous rocks along the west coast of Spitsbergen have been subjected to at least three major deformational phases (Harland, 1978; Harland et al., 1979; Birkenmajer, 1981). The first event, D1, is inferred to have occurred during the Caledonian Orogeny in Early Silurian time and involved eastward overthrusting and biotite to garnet grade metamorphism. Radiometric dating of glaucophane schists found in the Vestgötabreen Complex, using whole rock potassium/argon techniques, indicates apparent ages between 620 and 410 m.y. with minimal recrystallization during the Tertiary (Horsfield, 1972). These ages correlate with those of other highly deformed metamorphic rocks outcropping in Spitsbergen, (Hjelle et al., 1979) and help to support a Caledonian age for the D1
event.

The second event, D2, is believed to have taken place during Late Silurian to Devonian time and caused large-scale folding, thrusting, and associated sub-greenschist metamorphism in upper package rocks. Recrystallized biotite and muscovite along with small amounts of chlorite have been found in the Bullbreen Group. Harland (1971) attributed this folding to sinistral transpression along large-scale fault zones. At that time, Spitsbergen was probably located just north of Greenland.

A third phase, D3, resulted in northeastward thrusting and retrograde metamorphism during the Tertiary. Lowell (1972) attributed this event to a dextral transpression motion, which moved Svalbard away from northern Greenland into its present-day geographic position.

In the St. Jonsfjorden area, the first two phases, D1 and D2, are most significant and have produced the dominant structural characteristics present in the rocks. In addition, field relationships between observed deformation fabrics indicate that the D2 and D3 events postdate the penetrative deformation of the lower package. D2 appears to be the dominant deformational event affecting the Bullbreen Group.

2.3.2 Structural Relationships in St. Jonsfjorden

Weiss (1953) published the first structural analysis of St. Jonsfjorden. He identified fold axes of the Bullbreen
Group as having an east-west trend with a westward plunge but did not separate the group from the lower rock package. Weiss related these structures to Caledonian deformation. Hjelle et al. (1979) separated the Bullbreen Group from the lower package with a low-angle fault, but did not develop a distinct deformation history for the Bullbreen Group. This latter group of workers also noted the overprinting of a compressional crenulation cleavage on earlier deformational fabrics. The absence of kink-bands or tight folding in the Permo-Carboniferous rocks of St. Jonsfjorden led these workers to tentatively place the deformation event resulting in the fabric development of the Bullbreen Group, D2, in late Caledonian time.

2.3.3 Structures of the Lower Rock Package

The first deformational event in the field area, D1, formed the dominant structures present in the lower package. Primary sedimentary features are discerned only with difficulty in most outcrops of the lower package. Bedding surfaces are generally indicated by graded bedding and cross-bedding. Folds are tight to isoclinal and have fold axis trends ranging from northwest to southeast with moderate plunges. Poles to axial-planar foliation also have a range of orientations. They predominantly plunge steeply to the northeast and some poles have a shallow to moderate plunge to the southwest. Harland (1978) inferred general eastward thrusting coupled with 200 kilometres of east-west
shortening.

In the central region of St. Jonsfjorden, fold axes and lineations have been deformed by a later deformation event, the timing of which is uncertain. As a result of reorientation by this later deformation event, these earlier linear fabrics have variable trends ranging from northwest to southwest in that area of the fjord.

2.3.4 Structures of the Upper Rock Package

In the field area, a limited number of Bullbreen Group exposures were available for mapping and sampling. Of these, the principal outcrop areas, Ankerfjella, Bulltinden, and Holmesletfjella, were studied. Bedding orientations are highly variable at outcrop scale as a result of tight, minor folding. Bedding attitudes were determined by detailed mapping and are shown, along with other structural data for the Bullbreen Group, in Figure 12. Folds present in the Bullbreen are tight to isoclinal, but have a much more consistent fold axis orientation than those of the lower package; they generally plunge shallowly to the west-northwest and in places, to the east-southeast. Axial-planar cleavage, formed by pressure solution, appears in hand specimens and thin section as darkened seams of an insoluble residue (Fig. 13). Poles to this cleavage are strongly clustered and plunge steeply to the northeast. Exceptions to these fabric orientations occur in some areas at Bulltinden, where some fold-axes plunge to the
Figure 12. Equal-angle stereographic plots of structural orientation data for the sampled localities of the Bullbreen Group.
Figure 13. Enlarged sketch of a thin section cut perpendicular to cleavage. The sample was taken from Ankerfjella. Bedding planes appear as slight color variations in thin section; here, they are represented by faint, curved lines. The dark, heavy lines are pressure solution cleavage planes, marked by insoluble residue seams. The stippled areas represent minor calcite-filled fractures. (8x magnification)
east-southeast and cleavage dips shallowly to the southeast.

During D2, horizontal movements are inferred to have taken place along large, isolated zones of the lower package. In the upper package, thrusting of overlying Bullbreen rocks occurred in a northeastward direction. The basal zone is often structureless when seen in outcrop. Minor folding of the lower members of the Bullbreen Group did not extend into the basal zone. The displacement occurring along the zone was associated with overturned folding and cleavage development above the basal zone.

The detailed mapping has confirmed the presence of major overturned folds in the Bullbreen Group (Figs. 15 and 16). Recognition of this stratigraphic repetition has resulted in a reduction of the overall thickness of the unit. Estimates by earlier workers of 1200 metres (Hjelle et al., 1979) have been lowered to approximately 475 metres (Ratcliffe, 1985). In Figure 15, the base of the Bullbreen Group section at Ankerfjella shows the imbrication of basal Bullbreen lithologies. In Figure 16, the overturned limb of a large fold, the Copper Camp fold, on the southeastern side of Bulltinden is shown. A consistent northeasterly direction of thrust movement is supported by these two cross-sections. This direction is also indicated by southwest-dipping cleavage implying compression in a northeast-southwest direction.

A gentle downwarp with a north-south axis refolds the Bullbreen lithologies at central Ankerfjella. The formation
Figure 14. Enlarged geologic map of the western end of the St. Jonsfjorden area showing lines of cross-sections.
Figure 15. SW-NE section along Line A-A' of Figure showing imbrication of the basal zone and northwest-vergent minor folds of the Bullbreen Group at Ankerfjella.
Figure 16. SW-NE section along Line B-B' of Figure showing the overturned limb of the Copper Camp fold and northward-vergent minor folds at southern Bulltinden.
of this synform, with dips of the limbs at a maximum of 20 degrees, postdates the regional D2 event and reorients D2 structures in that area. This feature has also been mapped by previous workers (Hjelle et al., 1979).

The D2 event in St. Jonsfjorden also produced at outcrop scale, a locally extensive system of fractures which are filled with fibrous carbonate crystals and occur principally in the mudstones of the upper rock package. These extension veins have opened in a direction parallel to the axes of mesoscopic D2 folds. Poles to the planes of these veins lie very close to the orientations of major D2 fold axes and bedding-cleavage intersection lineations (Fig. 12). In addition, the fibers often show a sigmoidal form which indicates their growth during progressive deformation (Durney and Ramsay, 1972) making the fibers a syntectonic deformation feature.

The Bullbreen Group also contains a series of semi-brittle features which offset earlier-formed D2 structures and in places cut across the fibers in extension veins. These microfaults are small-scale normal faults and are generally parallel to the planes of earlier-formed fibrous calcite veins. These observations indicate the existence of similar extension directions during the formation of both the extension veins and the microfaults.

In the area of Bellsund, 120 kilometres south of St. Jonsfjorden, Kowallis and Craddock (1984) describe two major deformational events which may be correlated to the first
two deformational events of the St. Jonsfjorden area. Their first event resulted in the formation of a flattening fabric in conglomerates found in their field area. Large fold structures formed during this event were overprinted with deformation fabrics formed during the later event. The second major phase of deformation, Late Caledonian to possibly Early Carboniferous in age, produced folds which plunge gently to the west-northwest and an axial-planar foliation which dips gently to the southwest. Compression acting in a northeast-southwest direction has been inferred from the orientation of the foliation formed during this second event. These observations are generally consistent with structures formed in the rocks of the St. Jonsfjorden area.

2.3.4 D3 Structures

Superimposed on all upper and lower package rocks are planar D3 fabric elements which are generally vertical and strike north-south throughout the field area (Hjelle et al., 1979). In the lower package, this event has produced localized areas, one to two metres across, with tension gash systems and kink bands. In the upper package, kink bands are well developed in the mudstone exposures near Bulltinden and at Holmesletfjella.
CHAPTER THREE
DEFORMATIONAL CONCEPTS

3.1 Finite Strain

Deformation is a process whereby points in a medium undergo displacement relative to each other; the distance between any two points is generally altered and the angle between any two non-parallel lines is generally changed (Durney and Ramsay, 1972). When these displacements can be measured, the amount of strain a rock has undergone can be determined.

The techniques of strain analysis provide a means of quantifying the distortions that rocks have experienced. Such techniques are based on the mathematical and statistical treatment of linear, angular, and spherical elements found in the rocks. Deformed fossils, pebbles, and ooids have commonly been used to measure the cumulative strain. In addition, features which form and grow as deformation takes place, such as fractures filled with crystalline material or pressure shadows, allow the incremental strain history to be determined.

A rock mass is rarely isotropic and strains in a rock usually vary in their orientation and magnitude. Displacements, therefore, are generally not orderly and rock strain is characteristically heterogeneous on all scales (Wood and Holm, 1980). If the variation in strain is somewhat regular, a heterogeneous strain state may be
subdivided into smaller strain fields over which strain is assumed to be homogeneous. This assumption is necessary in order to apply the techniques of strain measurement to most rocks. Homogeneous strain is defined as the condition whereby all sets of initially straight, parallel lines remain straight and parallel after deformation (Ramsay and Huber, 1983, p. 284). These properties are expressed by the grid systems in Figure 17. The squares in the orthogonal grid, A, are transformed into identically shaped and identically oriented parallelograms in B. For the condition of homogeneous strain, displacement vectors, which indicate the local translation of material points are similar and a constant displacement gradient exists across a rock mass (Hobbs et al., 1976, p. 24). In order to quantify rock strain, the scale and the area within which the strain is considered to be homogeneous should be indicated (Wood and Holm, 1980).

3.2 Strain Parameters

As rocks deform, the material will undergo a shape change. This change can be defined in terms of an extension. In any given direction in a rock, the change in length of a line as a result of deformation is compared to the length of that line before deformation. A negative extension denotes a contraction or decrease in length whereas a positive extension indicates an increase in length.
In order to represent the finite or cumulative state of strain within rocks, the concept of a strain ellipse is employed. For an assumed state of homogeneous strain, a circle of unit radius imposed upon the surface of an undeformed material will, after deformation, have an elliptical shape. Various directions across this initial circle may experience a positive or negative extension. The two mutually perpendicular directions coinciding with the major and minor axes of the strain ellipse experience maximum and minimum extensions, respectively (Fig. 17). The resulting ellipse is called the finite strain ellipse. The values of the major and minor semi-axes of this ellipse, \((1+e_1)\) and \((1+e_2)\) represent the principal finite strains and \(e_1\) and \(e_2\) are the principal extensions.

The geometric study of strain can be expanded into a three-dimensional analysis within a rock mass through a combination of two-dimensional data from differently oriented surfaces. The concept of a sphere of unit radius, rather than a circle, is employed. This imaginary sphere in an undeformed rock is transformed into an ellipsoid as a result of deformation, the finite strain ellipsoid. The directions of the three mutually perpendicular axes of this ellipsoid indicate the directions of maximum, intermediate, and minimum extension in the rock. These directions are also called the three principal axes of finite strain (Ramsay, 1967, p. 122). The long axis of this ellipsoid, \(X\), is parallel to the maximum extension direction. The
Figure 17. Sketch of two grid systems illustrating the geometric features of homogeneous strain. The reference directions, X and Y, are the same for both cases. A. Undeformed orthogonal grid with unit circle. B. Deformed grid with strain ellipse. The length of the long axis equals \((1+e_1)\); \(e_1\) is a positive extension. The length of the short axis equals \((1+e_2)\); \(e_2\) is a negative extension. (after Ramsay and Huber, 1983, p. 284).
intermediate and short axes of this ellipsoid are $Y$ and $Z$, respectively. It is commonly assumed that the $X-Y$ plane of the finite strain ellipsoid is parallel to the flattening fabric developed in deformed rocks, usually the plane of cleavage (Hobbs et al., 1976, p. 233).

3.3 Incremental Strain

A greater understanding of the kinematic evolution of a region can be gained by analyzing the deformational changes which took place in rocks over a period of time. This involves the sequential, incremental strain changes that a rock was subjected to as it progressed toward its final strain state. Unfortunately, incremental strains are rarely known, because evidence of their magnitude and orientation are not generally recorded or preserved in deformed rocks.

During deformation, a rock passes through a series of geometrical changes. A structure initiated early in a deformation process may have its form modified later in the same event. In the course of progressive deformation, the previously defined unit circle imposed on a rock will undergo a series of shape changes. The axial ratio will vary as different ellipses are created (Fig. 18). Additional amounts of distortion are needed to convert the ellipse from one form to the next. This additional amount can be characterized by imposing on the deforming rock new unit circles at various times in the displacement process. In going from one ellipse to the next, the new unit circle
Figure 18. Two-dimensional progressive deformation sequence. The shapes of the strain ellipses indicate the total strain at successive periods during the deformation process. The change from one ellipse to the next reflects the incremental strain the rock experiences during that time. For example, a unit circle at Time-6 becomes an incremental strain ellipse at Time-7, and records only the distortion between these two stages (after Durney and Ramsay, 1972).
will record that increment of strain and is referred to as the incremental strain ellipse. In rotational strain, the axes of the incremental strain ellipses are not parallel to the axes of the ellipse recording the cumulative strain up to that point. Ramsay and Graham (1970) have shown that natural strain sequences are commonly rotational; therefore, as a rock deforms, successive strain ellipses will show a systematic variation in orientation. Progressive deformation is a continuum and the incremental strain concept is a device used to summarize the strain history. The incremental and cumulative strain ellipses are mathematically related by matrix multiplication (Appendix B).

3.4 Pressure-Solution Processes

Pressure solution is the dissolution of minerals under non-hydrostatic stress (Durney, 1972). During deformation, soluble minerals in areas of high mean stress can be dissolved and the solution may travel by differential chemical transfer through both pores and micro-fractures into areas of low mean stress (Fig. 19). The transfer takes place by transportation of dissolved ions in an aqueous phase through pores or along grain boundaries.

Pressure solution results in the formation of discrete, undulating surfaces defined by dark, insoluble residues. Tectonic pressure solution occurs on surfaces statistically perpendicular to Z, the minimum strain ellipsoid axis.
Figure 19. Block diagram illustrating the sequence of events leading to the development of pressure solution cleavage and crack-seal veins. X and Z are greatest and least principal strain axes, respectively. A. Undeformed rock. B. Fracture develops parallel to the X direction. C. Fibrous crystals filling the fracture grow parallel to X and insoluble residue seams form perpendicular to Z. D and E. Continued growth of crystals parallel to X on either side of median line of vein and development of insoluble residue seams. F. Observed relationships between pressure solution cleavage and crack-seal vein development in the study area.
(Durney, 1972). As the process occurs, mineral differentiation takes place. The solution and transportation of soluble material such as quartz or calcite takes place and relatively insoluble clays, micas, and heavy minerals remain in place and accumulate. These minerals left behind may be rotated into a preferred orientation and give rise to planes of weakness during further deformation.

According to the theoretical discussion by Durney (1972), the source area for vein-filling material is under high stress and loses volume because of the dissolution and removal of soluble material. At the same time, this solute moves in the X direction and crystallizes in veins and pressure shadows. These veins and pressure shadows may expand in the X direction while pressure solution activity occurs in the adjacent rock mass. Also, fractures generally widen in the X direction because a minimum amount of work is needed for the vein to expand against the rock in this direction. Often, naturally deformed rock features, such as fossils or ooids, are dissolved in the Z direction and show mineral growths in the X direction. Weyl (1959) discussed further the details of the parameters of pressure solution such as solute transport, stress distributions, and energy of mineral crystallization.

3.5 Measurement of Extension Using Veins

The presence of veins in rocks indicates a positive extension; points originally in contact are now separated by
crystalline material filling in the fractures. The concept of an extension is employed as a standard way to measure a change in length in a given direction. This extension measurement is one of many ways to calculate strain in rocks. The general formula for an extension is given by:

\[ e = \frac{L_1 - L_0}{L_0} \]

\( L_1 \) - new length of traverse

\( L_0 \) - original length of traverse

This formula is adapted to the present strain analyses in the form of:

\[ e = \frac{\Delta V}{L_0} \]

\( \Delta V \) - change in length of vein material

\( L_0 \) - original length before vein material was added

The distance across the Bullbreen Group calcite veins can give an indication of the amount of extension that has occurred perpendicular to the vein trend. If both the amount of wall rock \( L(\text{rock}) \) and vein material \( L(\text{vein}) \) across a given traverse is measured, the percentage change in length along that traverse resulting of vein formation can be determined. The formula for this extension, \( e \), is given by:

\[ e = \frac{\Delta V}{L_0} = \frac{L(\text{vein})}{L(\text{rock})} \]

When veins are filled with fibrous material, the orientation of the fibers can define more precisely the extension direction as well as the amount of extension.
Fiber orientations can be determined by optical methods or by direct measurement. The crystallographic axes of crystals may have specific relationships to the strain fields in which they form, e.g. calcite fibers will grow with their C-axes parallel to the maximum extensional strain direction (Winsor, 1983).

In the case of sigmoidal fibers, the amount of fiber growth in a given direction can be measured and related to the amount of previous growth to find the incremental extension. The formula for this incremental extension, \( e_i \), is given by:

\[
e_i = \frac{\Delta V}{L_0} = \frac{L(\text{new})}{L(\text{old}) + L(\text{wall})}
\]

- \( L(\text{new}) \) - length of fiber segment in a given direction
- \( L(\text{old}) \) - length of previously formed fiber segment in the same direction
- \( L(\text{wall}) \) - length of existing wall rock in the same direction

(Ramsay and Huber, 1983, p. 251)

The selection of \( L(\text{wall}) \) is often arbitrary and will greatly influence the calculated \( e_i \) values. A large \( L(\text{wall}) \) value will give smaller \( e_i \) values.
CHAPTER FOUR

DEFORMATION IN THE BULLBREEN GROUP

4.1 Tectonic Cleavage

The spaced deformation fabric in the Bullbreen Group is a tectonic cleavage formed by pressure solution processes. The fabric, indicated by darkened, parallel planes, transects bedding (Fig. 13) and the extension vein filling (Fig. 20). This fabric is also axial-planar to D2 folds. In addition, the fibers of the extension veins are seen to lie within the plane of cleavage. This relationship is discussed further in Section 4.4. Additional evidence for pressure solution activities in the Bullbreen Group are pyrite pressure shadows, sutured grain boundaries, solution-pitting of grain surfaces, and the mineral fillings of extension veins.

The presence of calcite-in solution is indicated by calcite mineral flats (Fyfe et al., 1978, p. 288). Lenticular deposits of calcite, one-half to two meters across and 5-15 cm thick, are found parallel to the mudstone layers. Migrating fluid under pressure is trapped by the relatively impervious mudstone strata and the precipitation of minerals from these accumulated pore fluids results in the formation of calcite pods and lenses.
Figure 20. Photomicrograph of elongate calcite fibers. The view is nearly parallel to the C-axes of the fibers. The dark lines extending across the photograph are pressure solution seams. The scale is as shown.
4.2 Syntectonic Extension Vein Development

Deformation of rocks in the shallow parts of the crust under brittle conditions can result in the development of subparallel, regularly spaced systems of extension fractures. These fracture spaces are sometimes filled with minerals, often with a fibrous habit, formed by precipitation from saturated pore fluids or redeposition of pressure-solution-derived material. These fibrous extensional features may reflect large finite elongations and can record total strains of several percent and local extensions in excess of 50 percent (Ramsay, 1980). Such features occur most frequently in rocks subjected to deformation at metamorphic grades no higher than upper greenschist facies. At higher grades, the fracture fillings recrystallize, losing their optical individuality and their fibrous shape.

Internal strains in a rock mass may increase as a result of tectonic activity until a critical level is reached and a fracture is created (Ramsay, 1980). Such fractures are subsequently filled with crystalline material precipitated from a fluid phase present in the rock. Fluids circulating through the rock contain elements in solution which are derived from the surrounding rock mass. The crystallization of solid material to seal a fracture indicates that either the fluid containing such minerals must continually flow through the fissures or that solid material is continually dissolved and transported through
the vein walls into the fluid (Ramsay, 1980).

When the void spaces are filled with solid material, stresses can be transmitted across the vein and vein walls. As the stresses build up and again exceed the rock's critical tensile limit, new fractures may form between the existing vein material and the vein wall or in the centre of the vein. The sealing process occurs again, filling in the newly created voids. This repetition of fracture formation followed by mineral precipitation is called the crack-seal process (Ramsay, 1980). Syntectonic vein growth with the formation of fibrous crystals can best be explained in terms of this mechanism. Syntectonic vein fibers will continue to record new increments of rock extension as long as there is enough material in solution to fill any newly created spaces.

These crystals connect points on either side of the vein that were in initial contact with each other before fracture formation. During syntectonic vein development, an open space in the rock exists for only a very small period of time. The circulating pore fluids are saturated with respect to the precipitated minerals and when the rock fractures, the pressure decrease causes nearly instantaneous precipitation. In contrast, crystals growing in an open cavity increase in size toward the center of the cavity and usually exhibit euhedral terminations. Their growth directions bear no relationship to the displacements that may have resulted in the formation of the cavity. Although
freely growing crystals may be elongate, they rarely show the very elongated form with extreme length-to-width ratios of the crystal fibers of extension veins (Ramsay and Huber, 1983, p. 236).

4.3 Syntectonic Vein Systems

A geometric analysis of structures, such as boudin necks and extension veins, can provide very detailed information of progressive strain increment sequences. In order to correctly interpret the strain sequence, it is necessary to differentiate between four major types of syntectonic veins. The geometry and mineralogy of these veins are variable and depend on their mechanism of formation and growth which forms the basis for classification. Each type of vein contains markers that identify its growth pattern and allow the incremental strains recorded by the fibers to be measured.

Curved fibers in these veins are the result of changes in the direction of progressive opening of the fissures (Ramsay, 1980). The fibers record the strain axis orientation with respect to the vein walls under the deformational conditions prevailing at the time the increments are added (Winsor, 1983). The following descriptions are taken from Durney and Ramsay (1972) and Ramsay and Huber (1983, p. 238-249).
4.3.1 Syntaxial Veins

Crystalline material found in these veins is compositionally identical to that of the vein walls; such as quartz veins in sandstone or calcite veins in limestone. When the wall rock contains a variety of minerals, fibers of several compositions grow together in a sub-parallel arrangement. The shapes of the vein walls are irregular and controlled by the shapes of crystal boundaries making up the walls. The fibers grow in two distinct groups; each group is attached to one of the vein walls and shows a specific crystallographic relationship to crystals found in that corresponding wall (Fig. 21, A). The vein filling is an overgrowth on original wall rock crystals and is in optical continuity with these wall crystals. When the fracture widens, a break occurs in the center of the vein between these two crystal groups and fiber growth occurs along this central fracture.

The two fiber groups meet at a centrally located suture line and when they are curved, appear to have a rotational symmetry about the median line. Fibers, whether straight or curved, are always perpendicular to the walls at the vein-wall contacts. In some veins, the fibers become wider towards the center of the vein, as some crystals with a more favorable crystallographic orientation grow at the expense of adjacent crystals.
Figure 21. Principal features of the four main types of fibrous vein systems showing the relationship of the composition and crystallographic orientations of vein fibers to wall rock crystals. The black and white unstippled areas represent crystals of the same mineral but with different crystallographic orientations. The stippled areas are crystals of another species (after Ramsay and Huber, 1983, p. 241).
4.3.2 Antitaxial Veins

These crystals do not form as overgrowths on vein wall crystals and therefore have no fixed crystallographic relationship to crystals in the vein walls. Fiber composition in these veins will depend on adjacent rock composition as the vein material is commonly derived from the host rock by pressure solution. Fibers extend, with crystallographic continuity, from wall to wall. The central median line is well defined with wall rock fragments and parallels the outline of the walls (Fig. 2l, B). This median line marks the first increment of fiber growth during the first crack-seal event. Often, smaller-sized fragments making up less noticeable inclusion trails are found on either side of the central suture. These wall-rock trails mark successive openings along the vein-wall contacts by the crack-seal process.

When a fracture widens, breaks in the rock occur on both sides of existing vein material and fiber growth occurs by addition of vein material along the vein-wall contact. The faint trails of wall rock inclusions found on either side of the median line represent these distinct fracturing events along the vein-wall contacts. Country rock is removed as the wall-vein seal is broken and incorporated into the fibers. When fiber growth is competitive, the later-formed fibers at the vein-wall contacts are wider than fibers in the center of the vein. In the case of sigmoidal fibers, the fibers in the center of the veins are usually
perpendicular to the vein walls and those at the margins are oblique to the walls.

4.3.3 Composite Veins

This system consists of three groups of fibrous crystal species; two fiber groups located along the vein walls separated from each other by a central fiber group in the middle of the vein (Fig. 21, C). The wall rock and marginal fibers are usually of the same mineral species and show crystallographic parallelism to the crystals in the vein walls. The central fiber group has a centrally located median line of rock fragments and exhibits characteristics similar to those of antitaxial veins. The median line is parallel to the vein walls as this was the first area of fiber growth. The two fiber groups on the margins of the veins, one group along each wall, are comparable to fibers forming by syntaxial growth. Composite fibers are perpendicular to vein walls along the vein-wall contacts and near the central median line and are oblique to the vein walls along the interface of the two zones. As a fracture widens, breaks occur along the interfaces and fiber increments are added along these zones.

4.3.4 "Stretched" Crystals

These crystals have similar mineralogy to that of the wall rocks. The fracture initiates through grains rather than around them and the overgrowths form on these broken
crystals. The fibers grow in an optically continuous crystal across the vein; with the fibers connecting two separated halves of an originally whole grain (Fig. 21, D). The central suture line of these veins is not marked by wall-rock inclusions. Fiber growth occurs by the non-uniform addition of crack-seal increments along the centrally located line. The fibers consist of small block-like elements of unequal length which are added to the ends of existing fibers near the center of the vein.

4.4 Extension Veins of the Bullbreen Group

The strain indicators used in this study to determine part of the strain history of the Bullbreen Group are the extension fractures found principally in the mudstones of this upper rock package. The following descriptions are based on the limited number of exposures in the field area containing extension veins.

The localities indicated in Figure 22 are the principal outcrops containing the areas of greatest visible development of extension veins. Locality A consists of rocks exposed on either side of a small stream which flows southward down the steep, southern side of central Ankerfjella. Most of the rocks here are mudstones and the exposure surfaces are cleavage planes. Veins in the mapped areas are 2.5 to 10.0 cm long and 0.5 to 2.5 cm wide. The veins are spaced 2 to 10 cm apart. Locality B is a similar, but smaller, stream valley located approximately 500 m to
Ankerfjella
A - Samples D14, D17, D18, D25, D26, D137
B - Samples D47, D49
Holmesletfjella
C - Samples D57-D59, D62, D64, D67, D72-D75, D79, D81, D98, D100, D144, D66
D - Samples D111, D118, D119
Bulltinden
E - Samples D82, D85, D91
F - Sample D127

Figure 22. Map of the western end of St. Jonsfjorden showing sampled localities.
the west of locality A. The vein exposures here are isolated, with vein spacing up to 0.8 m apart. Cleavage orientation at locality B is variable as a result of gentle refolding.

Locality C is the largest of scattered exposures located in the moraine just north of Bullbreen Glacier. Here, the exposures again consist of southwestward-dipping cleavage planes (Fig. 23). The mapped veins are 6 to 18 cm long and 0.5 to 2.0 cm wide and are spaced 10 to 20 cm apart (Fig. 24). The rocks of locality D, similar to those found at locality C, are found at the mouth of a meltwater stream flowing from Bullbreen Glacier into St. Jonsfjorden. These exposures are in places highly fractured and appear to have been displaced a few centimetres by ice. A lack of rotation is evident because of consistent cleavage orientation.

The Bullbreen exposures at locality E are in a river valley at northeastern Bulltinden. Only a few of the exposures here contained extension veins. Outcrops at locality F are located at the top of central Bulltinden. At both localities E and F, the cleavage dips to the southwest. The very small size and scattered distribution of exposures at localities B, D, E, and F prevented the detailed mapping necessary for the local finite strain analysis.

At the sampled localities of Ankerfjella and Holmesletfjella, several stratigraphic sections, approximately 1.5 m long were measured and the relative thicknesses of mudstone to siltstone were calculated. The
Figure 23. Photograph of a typical outcrop section at Holmesletfjella. The view is almost parallel to bedding. The lens cap is 5 cm across.
Figure 24. Photograph of weathered cleavage planes at Holmesletfjella, Locality C on Figure 22, showing the calcite extension vein outcrop pattern. The view is perpendicular to the exposure surfaces. The scale is 15 cm long.
mudstone-siltstone ratio at Ankerfjella, locality A, varies from 2.5 to 8.0. At Holmesletfjella, locality C, this ratio varies from 0.1 to 0.3. Section measurement was not possible at the other localities because of the limited amount of the exposed portion of the outcrops.

As one vein tip was encountered in an outcrop, another adjacent, parallel vein was often found propagated down the outcrop surface. The dying out of a vein is related to the accommodation of strain at some other point in the rock mass. Segall (1984), in his study of extension fractures in the Sierra-Nevada Range, showed that because of mechanical instabilities created in the rocks during deformation, vein systems are more likely to develop quasi-statically, in a series of closely spaced fractures, rather than as one, long and continuous fracture (Fig. 25).

The surfaces on which the veins are exposed are cleavage planes and initial observations showed the length of the crystals found in these veins lies, for the most part, parallel to the planes. As cleavage forms, the crystals grow parallel to cleavage and track the maximum extension direction, X, within these cleavage planes.

Closer-observations with a petrographic microscope showed that the cream-coloured calcite crystals filling these fractures have an elongate, fibrous habit (Figs. 26 and 27) and are continuous across the entire width of the vein. The fibers have both straight and sigmoidal forms. As the microscope stage was rotated under crossed Nicols, an
Figure 25. Photograph of a hand sample taken from Ankerfjella, Locality A on Figure 22, showing the outcrop pattern of several extension veins. The scale is as shown.
Figure 26. Photomicrograph of sigmoidal, elongate calcite fibers. The section is cut parallel to cleavage. The scale is as shown.
Figure 27. Photomicrograph of sigmoidal, elongate calcite fibers. The section is cut parallel to cleavage. The scale is as shown.
extinction band was seen to pass through the crystals. The veins also contain a centrally-located median surface (Figs. 28 and 29) consisting of wall rock inclusions within the fibers. This median surface generally parallels the vein walls and the sigmoidal, fibrous crystals are generally symmetrically arranged about this surface (Fig. 26). Often, faint trails of additional wall rock inclusions are found within the fibers, parallel to and on either side of the median surface.

At each locality, the straight, central segments of sigmoidal fibers are parallel to the straight fibers with a non-sigmoidal form. This indicates that when the vein initiation process occurred, the extension direction present was consistent in orientation. The veins with straight fibers stopped widening, whereas those with sigmoidal fibers continued to develop. Of the 120 samples taken, approximately 70 to 80 percent of the veins contain fibers with a sigmoidal shape; in these veins the fiber segments adjacent to the median line are at an angle to the fiber segments near the vein walls. The fibers formed at the tips of these fractures are straight and have the same orientation as the fiber segments of sigmoidal fibers found along the vein-wall contacts of the same vein (Fig. 30). Fiber segments at the sides of the veins are oblique to the vein walls whereas those fiber segments found in the middle of the vein are nearly perpendicular to the vein walls.

Some fibers, however, show an asymmetric growth
Figure 28. Photograph of a hand sample from Ankerfjella, Locality B on Figure 1, showing the well-developed median line of a calcite extension vein. The scale is as shown.
Figure 29. Photomicrograph of sigmoidal, elongate calcite fibers showing a well-developed median line of wall rock inclusions. The section is cut parallel to cleavage. The scale is as shown.
Figure 30. Enlarged sketch of antitaxial fibers in an extension vein, sample D127 from Bulltinden. Straight fibers are found in the vein tip, at the bottom of the sketch. These straight fibers have the same orientation as the latest-formed segments of sigmoidal fibers found along the vein walls.
Figure 31: Photograph of a typical antitaxial extension vein developed in the exposures at Ankerfjella. A scale in mm is to the right.
pattern. Fibers on one side of the centrally-located inclusion line appear to be relatively straight, whereas those found on the other side have both a straight and a sigmoidal shape. The curved portions of the fibers are longer than the straight fiber segments and the straight segments on both sides of the median line are the same width. These fibers probably formed as a result of fracturing occurring only along the vein-wall contact adjacent to the sigmoidal fibers. The other vein-wall contact adjacent to the straight fibers did not continue to fracture once the straight fibers had formed.

The characteristics of the fibers indicate that the veins found in the Bullbreen Group are antitaxial according to the criteria presented in Section 4.3. The fiber formation in these veins is outlined in Figure 32. Fibers filling in the initial fracture will grow in a direction parallel to the earlier incremental extension direction. As the rock accommodates further strain increments, the fractures may continue to open. The direction in which they open can be either normal or oblique to the vein walls and will depend on the orientation of the incremental strains existing at the time the fracture increases in width. The orientation of the maximum extension direction, X, existing during the time a fracture widens may not be the same orientation as the original X direction present during the fracture’s initiation. The walls of the fracture may not be perpendicular to this later extension direction. However,
Figure 32. Four simplified sketches of antitaxial fiber development showing possible relationships between the maximum extension direction, vein walls, and fibrous crystals. A. Fracture is initiated and begins to widen. B. Fibers grow in fracture parallel to the X direction. After B, either one of the events indicated by the large arrows may occur. C1. Incremental extension direction changes as fracture widens. New fibers grow parallel to new extension direction and are oblique to vein walls. C2. Incremental extension direction remains constant as fracture widens. New fibers continue to grow parallel to X and remain perpendicular to vein walls. Note that in all cases, the vein walls retain the same orientation.
the orientation of the fibrous crystals filling the fracture will always parallel the existing X direction. The length and growth sequence of the fibers can be used to determine the incremental and cumulative finite strains associated with the widening of individual veins.
CHAPTER FIVE

STRAIN ANALYSIS USING SYNTECTONIC VEINS

5.1 Previous Studies of Syntectonic Fibers

The mechanisms of syntectonic fiber formation have been documented by earlier workers. A comprehensive explanation of the crack-seal mechanism of vein formation was given by Ramsay (1980) in his study of calcite veins in ferruginous limestones of the Aar Massif, Switzerland. Adjacent wall rock areas undergoing pressure solution were the likely sources for the vein material. In these extension veins, chlorite and calcite fragments occur within fibrous crystals as inclusion trails arranged sub-parallel to the vein walls. These trails are markers between more than 500 fiber increments added across a total vein width of 7.5mm. Individual inclusion crystals have a marked similarity in shape across the vein suggesting a common origin: They formed as new growths on wall rock grains and were separated from the wall rock by the crack-seal process.

Van der Pluijm (1984) discussed the morphology of a quartz vein found in a low-grade metamorphosed graywacke from Newfoundland. The C-axes of non-fibrous quartz crystals are nearly parallel to the long axes of the crystal shapes. The orientation of chlorite inclusions in the vein material was parallel to the orientation of grains in the foliated wall rock. He concluded that wall rock inclusions in fibrous veins form as syntaxial overgrowths on wall rock
mineral grains.

Syntectonic fibers provide detailed information concerning extension and rotation directions within rocks. Boudinaged limestones in the Liassic slates of Leytron, Switzerland contain fibrous veins of calcite and quartz. Incremental strains recorded by these fibers were determined (Durney and Ramsay, 1973) and compared with the fiber orientations. Graphs of incremental extension versus orientation were plotted for several samples. All major peaks on these plots were found to lie between N and NW, demonstrating that the greatest extensions in these rocks occurred in those directions. In addition, incremental strains computed from the fibers found in pressure shadows were very similar in magnitude to those calculated from the boudinaged veins.

Burg and Harris (1982) demonstrated that, although the walls of widening tension fractures may be oblique to the maximum extension direction, calcite fiber growth in extension veins parallels the maximum extension direction. The structural features they used to indicate this extension direction were fold axes and lineations found within the slaty cleavage planes. Casey et al. (1983) developed mathematical models which describe the progressive strains which contribute to the formation of chocolate-tablet structure. These models are based on crystal fiber growth which can form between the boudins. Ellis (1984) indicated that accurate strain histories of rocks may only be
determined if the incremental strains are homogeneous and the full lengths of the syntectonic fibers are preserved and observed.

Strain determinations are also possible from fibrous pressure shadows around pyrite and other rigid grains. Durney and Ramsay (1972) applied results of pyrite pressure shadow fiber measurements to structural studies in the Windhorn nappe, Switzerland, in order to formulate a preliminary interpretation of the strain history. During fiber growth, the initial incremental extension direction was oriented southeastwards. This was followed by an anticlockwise rotation of strain axes relative to the deformed rocks, after which the maximum incremental extension direction was oriented east-northeast to west-southwest. Fold axes in this area are generally oriented east-northeast to west-southwest. The fibers in the pyrite pressure shadows record an initial, strong elongation sub-perpendicular to fold axes followed by extension sub-parallel to fold axes. Movement directions and extensions determined from the fibers agreed well with data obtained from other structural features.

Incremental strains in the West Helvetic nappes of Valais, Switzerland have been fitted into a regional geologic perspective (Ramsay and Huber, 1983, p. 277). The earliest strain increments are found only in the structurally highest nappes, whereas late-forming increments are found through the deformed rocks. Highly irregular
incremental strains are recorded in the frontal parts of the nappes. This variation resulted from the differential movement of these nappes which were covered with a minimum of overburden. Extensions sub-parallel to the fold axes were found in the structurally higher units and were related to nappe transport over topographic irregularities.

5.2 Strain Analysis in the St. Jonsfjorden Area

To date, no published information concerning the strain history of the Bullbreen Group exists. Pebble dimensions were measured in tillites of the Comfortlessbreen Group by Hambrey and Waddams (1981). Their study concentrated on the relative deformation of the different clast lithologies rather than on whole rock strain. Bata (1982) analyzed deformed oolitic limestones from Prins Karls Forland. Ratliff (1985) has completed the most comprehensive study of strain to date in the St. Jonsfjorden area. The $R_f$/$\phi$ method of Dunnet (1969) was applied to deformed dolomite clasts from conglomerate horizons within the Holmesletfjella Formation to determine finite strain. The determined strain ellipse ratios are highly variable. In the $XY$ plane, ratios ranged from 1.02 to 1.73; in the $XZ$ plane ratios ranged from 1.74 to 2.78; and in the $YZ$ plane ratios ranged from 1.28 to 1.91. These variations in strain magnitude could not be related to areal or structural position in the Bullbreen Group. The accuracy of the strain magnitudes was judged to be low because the assumptions of an initial random clast
Figure 33. Equal-angle stereographic plots of calculated maximum and minimum finite strain directions and related structural data for the Bullbreen Group (from Ratliff, 1985).
distribution and homogeneous constant volume deformation required by the analytical method are not valid for the samples. The results did, however, indicate a consistent, sub-parallel relationship between D2 fold axes and the maximum extension direction of the deformed clasts (Fig. 33) and that the plane of flattening is parallel to cleavage.

5.3 Strain Measurements From Extension Veins in the Bullbreen Group

Two methods of strain analysis have been used in order to quantify part of the extensions at the sampled localities. The calcite extension veins at localities A and C were used to find estimates of local finite strain at Localities A and C. The sigmoidal fibers within the veins from all sampled localities were analyzed to determine relative incremental extension values and cumulative principal strains.

5.3.1 Local Finite Strain from Extension Veins

On the north shore at Ankerfjella, Bullbreen Group exposures consist principally of calcareous mudstones with interbedded siltstones (Fig. 34). These similar units are found at northwestern Holmesletfjella. The areas mapped contain the best-exposed cleavage planes showing the syntectonic veins. Only small scattered exposures of these veins occurred at the other localities. Most of the planar surfaces exposed in Localities A and C are cleavage surfaces. The local finite extension related to vein
Figure 34. Photograph of a stream valley at Ankerfjella, Locality A on Figure 22. The view is toward the north.
formation could be determined.

The cleavage surfaces were mapped at a 1:5 scale using a square grid, 0.3 metres on a side, and subdivided into 0.05 metre squares (Fig. 35). This grid was placed on the outcrop surface as parallel to the surface as possible. The grid was adjusted so that the measured average pole to the grid surface was sub-parallel to the pole to cleavage at that mapping site. Each vein falling within the boundaries of the grid was carefully drawn to scale and its length and maximum width were measured. When a grid area was completed, the corners of the grid were marked and the grid was moved adjacent to the area just mapped. This mapping procedure was carried out across the exposure surface to include as many veins as possible. Upon completing the mapping of one area of an outcrop, mapping was continued on nearby exposures.

Traverses were drawn across the maps, perpendicular to the long dimension of the exposed veins, to intersect as many veins as possible. Vein spacing in the outcrops was not uniform; the length of a traverse varied from 0.2 to 0.6 metres and the number of veins intersected varied between 4 and 12. Including several veins decreases large variability in finite strain that would be measured between just two veins. The extension in the direction of these traverses was calculated by the method shown in Figure 36. The end points of the traverse were chosen to be at the outside walls of the outermost veins defining the measured interval.
Figure 35. Photograph of the grid system used in the detailed mapping of the antitaxial extension vein exposures. The grid is 30 cm on a side and is subdivided by the orange-coloured string into 5 cm squares.
Figure 36. Sketch of cleavage surface explaining the calculation of finite strain.
Veins are outlined as they appear on a cleavage plane. Wavy lines indicate small seams of siltstone. The traverse line extends across the sketch to the outer edges of the outermost veins (here, Vein 1 and Vein 5). \( L_{\text{total}} \) is the total length of a traverse line. The sum of \( v \) terms represents total vein material present along the traverse line. The sum of \( r \) terms represents the width of wall rock along the traverse line. This second sum is labeled \( L_0 \) and represents the original length of the traverse before vein formation.

\[
\begin{array}{|c|c|}
\hline
\Sigma v + \Sigma r &= L_{\text{total}} \\
\Delta V &= e = \frac{\Sigma v}{\Sigma r} \\
(1 + e) &= \text{finite strain in direction of traverse} \\
\hline
\end{array}
\]
The sum of all vein widths (ΣV) intersecting this traverse was subtracted from the total length of the traverse L(total). This difference represents the original length of wall rock, (Σr) or Lo, across the traverse. Dividing the sum of the vein widths by the value of Lo gives the finite extension, e, along that traverse, as a result of vein formation. The local finite strains (1+e) for each traverse are given on a sketch map of locality A on Ankerfjella, Figure 38, and a sketch map of locality C at Holmesletfjella, Figure 40. Areas in these figures with no finite strains indicated showed minimal vein development or no exposure.

The traverses across the mapped surfaces were plotted as finite extension directions on an equal-angle stereonet, along with poles to the sketched surfaces (Figs. 37 and 39). For both mapped areas, the orientations of these finite extension directions generally plunged shallowly to the west-southwest with a few also having a shallow plunge to the southeast at Locality A. The maximum extension directions lie very close to the orientations of minor fold axes for both localities. The poles to the sketched surfaces in both mapped areas plunge steeply to the northeast.

Finite strains range from 1.1 to 1.95; representing a local 10 percent to 95 percent increase in length. In a comparison of equal areas of exposure from localities A and C, Locality A showed a greater amount of vein development.
Poles to mapped outcrop surfaces.

Directions of calculated finite extensions.

Figure 37. Equal-angle stereographic plots of the poles to mapped outcrop surfaces and the directions of calculated finite extensions at Ankerfjella, Locality A on Figure 22.
Figure 38. Sketch map of a stream valley at Ankerfjella, Locality A on Figure 22, showing the mapped locations of extensive antitaxial vein development. The number values represent the average calculated finite strains. Points on the graph to the right show how the mudstone-siltstone ratio varies in the measured outcrops along the stream valley.
Figure 3a. Equal-angle stereographic plots of the poles to mapped outcrop surfaces and the directions of calculated finite extensions at Holmesletfjella, Locality C on Figure 22.
Figure 40. Sketch map of exposed cleavage planes at Holmesletfjella, Locality C on Figure 22, showing the mapped locations of extensive antitaxial extension vein development. The number values represent the average calculated finite strains.
In the mapped areas of locality A, the finite strains ranged from 1.1 to 1.9 with an average of 1.35 and a standard deviation of 0.25. At locality C, the mapping consisted of one exposure where the finite strains were generally lower than at locality A. Two values were greater than 1.4 with the remainder ranging from 1.1 to 1.3. The average strain at locality C was 1.20 and the standard deviation was 0.10.

5.3.2 Discussion of Local Finite Strain

The finite strain analysis determines the finite extension in the rocks in a direction perpendicular to the plane of the veins. Poles to the planes of these extension veins (Fig. 12) are parallel to the traverse lines (Figs. 37 and 39). This direction is parallel to both straight fibers and the first-formed fiber segments found in the middle of sigmoidal fibers. The higher strains are found in areas of greater vein development. High measured values are due to more veins per equal length of traverse rather than closer spacing of veins along a traverse. The finite extension values were also generally higher when the fractured rocks contained higher percentages of mudstone (Fig. 38). Areas with a greater amount of mudstone contained more veins. Since the finite strain estimates depended only on these veins, areas with more mudstone give higher measured strain values. The mudstones accommodated some of the strain by fracturing. The more competent siltstones did not fracture; these layers may have taken up the strain by a more ductile
deformation mechanism.

Sketches were made by projecting the outcrop surface onto a single plane, the grid lines. This plane was close to but not always parallel to cleavage in that location. The maximum extension direction may lie at a small angle to, rather than parallel to, the sketched plane. The vein spacing was measured within the sketched surfaces; the actual vein spacing along the maximum extension direction may not be known. However, the angular difference is small so that the error introduced is insignificant when compared to the natural variability of the data.

Extension values may not represent the total finite extension in the measured directions. These strain values are based solely on extensions due to vein formation in a given direction. In reality, other deformation mechanisms have been active in the rock body. The faint system of probable D2 microfaults with a normal sense of displacement found throughout the Bullbreen Group offset the rock matrix between veins. The rock matrix between the veins has not simply been passively relocated during vein formation, but has also been extended. The presence of these offsets both within and around the veins indicates that these rocks have undergone further extension after vein growth was terminated. However, the faults have small displacements and even smaller extension in the traverse direction and probably do not greatly affect the measurements. These displacements do indicate a greater extension than that
recorded solely by the veins and so these veins only record a partial history of the total rock extension.

The discontinuous vein clustering and the variation in strain values within a relatively small area are indicative of the heterogeneity of strain at that scale. Finite strain values indicating up to nearly 100 percent extension show that large strains can be accommodated in a small rock volume by vein formation.

5.3.3 Incremental and Cumulative Strain

In all of the samples collected, continuous fibers grew across the entire vein width. Some of the veins contained sigmoidal fibers which indicated a changing incremental strain direction relative to the vein during vein development. Thirty oriented hand samples containing veins were cut along planes parallel to the cleavage. Table 1 presents the orientation data for these analyzed samples. These cut sections, with an orientation arrow, were mounted on thin section glass and ground down to a thickness of less than 50 microns. The ground sections were placed in a photographic enlarger and the projection of the vein walls and several complete fibers were traced on paper. The orientation arrow was also drawn on the sketch surface.

Fiber lengths in a particular direction are related to the amount of incremental strain in that direction. This length changed with orientation in the sketches. Using the method of incremental strain determination outlined by
### TABLE 1

SAMPLE ORIENTATION DATA

Listed next to each sample is the orientation of cleavage within that sample. All measurements were performed within these surfaces of known orientation.

\(124/16S = \text{strike of 124 degree azimuth} \quad \text{dip of 16 degrees to the south}\)

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Surface Orientation (Cleavage)</th>
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</thead>
<tbody>
<tr>
<td>Ankerfjella</td>
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<tr>
<td>Locality A</td>
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</tr>
<tr>
<td>D18</td>
<td>124/16S</td>
</tr>
<tr>
<td>D25</td>
<td>115/26S</td>
</tr>
<tr>
<td>D26</td>
<td>114/29S</td>
</tr>
<tr>
<td>D137</td>
<td>117/20S</td>
</tr>
<tr>
<td>Locality B</td>
<td></td>
</tr>
<tr>
<td>D47</td>
<td>135/11S</td>
</tr>
<tr>
<td>D49</td>
<td>100/22N</td>
</tr>
<tr>
<td>Holmesletfjella</td>
<td></td>
</tr>
<tr>
<td>Locality C</td>
<td></td>
</tr>
<tr>
<td>D57</td>
<td>157/20S</td>
</tr>
<tr>
<td>D58</td>
<td>120/24S</td>
</tr>
<tr>
<td>D59</td>
<td>166/16S</td>
</tr>
<tr>
<td>D62</td>
<td>131/21S</td>
</tr>
<tr>
<td>D64</td>
<td>164/25S</td>
</tr>
<tr>
<td>D66</td>
<td>132/27S</td>
</tr>
<tr>
<td>D67</td>
<td>126/18S</td>
</tr>
<tr>
<td>D72</td>
<td>142/23S</td>
</tr>
<tr>
<td>D73</td>
<td>132/22S</td>
</tr>
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<td>134/23S</td>
</tr>
<tr>
<td>D75</td>
<td>137/26S</td>
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<tr>
<td>D81</td>
<td>131/28S</td>
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<td>D98</td>
<td>108/19S</td>
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<tr>
<td>D100</td>
<td>129/15S</td>
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<td>104/17S</td>
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<tr>
<td>D111b</td>
<td>110/19S</td>
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<tr>
<td>D118</td>
<td>125/16S</td>
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<tr>
<td>D119</td>
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<td>Bulltinden</td>
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<td>Locality E</td>
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<td></td>
</tr>
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<td>D127</td>
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Ramsay and Huber (1983, p. 251), incremental strains recorded by these antitaxial growth fibers were calculated.

The sigmoidal fibers were divided into fiber segments using isogon lines (Fig. 41). Isogon lines connect points of equal inclination along a series of curved forms. The arrow at the top of Figure 41 is the orientation arrow for the cleavage plane along which the sample was cut. For each sketched vein, this arrow was used to determine a reference frame of equal-angle intervals for the measurements. Lines parallel to the intervals of the reference directions were drawn tangent to the sketches of the curved fibers. Isogon lines were then constructed across the fibers, connecting points of equal inclination, to delineate the fiber length between two chosen intervals. The lengths of several fibers segments bounded by the same isogon lines were averaged. The double-headed arrows at the bottom of Figure 41 indicate this average length of the incremental fiber segments. The orientations of the fiber segments were measured by determining a fiber segment's pitch on the cut surface of known orientation, the cleavage plane (Fig. 42).

As in the case of the local strain measurement, incremental strain estimates also involve the measurement of extension in a given direction. For each vein, a length of rock material existing in a certain direction when a fiber increment is added in that direction must be known. For the initial fiber increment in the centre of these veins, the length of existing material is assumed to be small segments
Figure 41. Sketch showing the method of dividing sigmoidal fibers into incremental fiber segments through the use of isogon lines. Lines drawn parallel to the 10 degree and 20 degree intervals are tangent to the curved fibers at specific points. Isogon lines, drawn to connect points of equal inclination, divide a fiber into segments.
Figure 42. Sketch explaining a geometric method of determining the orientation of fibers within the crack-seal veins. A. Block represents a hand sample cut parallel to cleavage. Fibers lie within the cut surface. B. Polished surface with orientation arrow mounted on thin section glass. C. Enlarged image of mounted fibers. Fibers are divided into segments using isogon lines as described in text. The angle between a fiber segment and the sample orientation arrow is measured. This angle indicates the pitch of that fiber segment within the cleavage plane. By knowing the cleavage plane orientation, each measured fiber segment is then plotted as a distinct point on an equal-angle stereonet, as shown in the Appendix A.
of wall rock material on either side of the vein. For later-formed fiber segments, the earlier-formed fiber length along with the length of small segments of wall rock parallel to the new fiber segment make up the existing material, L0 (Fig. 43). The length of these initial segments of wall rock is somewhat subjective and is generally left to the judgement of the analyst. The choice of a larger length of wall rock in the calculations leads to overall smaller calculated incremental strain values. A value of 0.5 mm in the direction of the first segment was chosen for the wall rock segment. Having a uniform initial wall-rock segment allows comparisons between veins and areas to be made. The strains associated with the same initial length of wall-rock are being determined in each case. The strain magnitudes are related only to that initial wall length and do not represent whole rock strains.

For a given angular interval, the length of previously formed fiber segments, sections of the vein walls, and added fiber increments were measured across several sections of the sketch and averaged. The incremental extension for each fiber segment, e, was calculated by dividing the sum of new fiber increments (La and Lb) measured on both sides of the median line in a given direction (Fig. 43) by the sum of pre-existing material $\left[ L(v) + 2L_{(ref)} \right]$ in the same direction.

For the incremental strain analysis, 6 samples from Ankerfjella, 19 samples from Holmesletfjella, and 5 samples
Figure 43. Sketch explaining the calculation of incremental extension from calcite fibers. In this figure, the incremental strain in the direction parallel to the reference arrow at the top of the sketch is measured. Lo is made up of the length of fiber existing at the time the fiber increments La and Lb were added, plus small segments of the wall rock. La and Lb represent incremental fiber lengths added, to existing vein fibers, in the direction of the reference arrow. The calculated extension value, $e_i$, indicates the relative amount of fiber growth in the reference direction (after Ramsay and Huber, 1983).
from Bulltinden were analyzed (Table 1). Samples with a greater number of fiber increments were chosen in order to determine a more complete strain history. For these antitaxial calcite fibers, measurements were started in the centre of the vein and progressed outward toward the vein walls. Extensions were determined for all fiber segment directions on each thin section.

For each analyzed sample, the fiber orientations and their associated incremental extension values were plotted on a stereonet. These diagrams are shown in Appendix A. In areas with more that two analyzed samples, two representative samples which show variation in both incremental extensions and fiber orientations are shown in Figures 44 through 47.

From Appendix A, the most complete and representative samples from localities A, C, D, and E were chosen. The presence of a similarly-oriented initial fiber segment at each of these localities allows the incremental $e_1$ values for these select samples to be averaged. These averages are shown in the summary diagram in Figure 48. Averaging smooths out individual data variability and gives a general amount of incremental extension in a given direction. The data from those areas with 1 or 2 samples (localities F and B, respectively) were not averaged and are presented in Figure 48. Each plotted fiber segment in Figure 48 has an associated average incremental extension value.

The C-axis orientations of these fibers were measured
Figure 44. Equal-angle stereographic plots of calcite fiber segment orientations and calculated incremental extensions for samples D18 and D26, locality A at Ankerfjella.
Figure 45. Equal-angle stereographic plots of calcite fiber segment orientations and calculated incremental extensions for samples D59 and D75, locality C at Holmesletfjella.
Figure 46. Equal-angle stereographic plots of calcite fiber segment orientations and calculated incremental extensions for samples D1llb and D1l9, locality D at Holmesletfjella.
Figure 47. Equal-angle stereographic plots of calcite fiber segment orientations and calculated incremental extensions for samples D82 and D85, locality E at Bulltinden.
Figure 48. Equal-angle stereographic plots of calcite fiber segment orientations with calculated average incremental extensions for the Bullbreen Group. The localities are as indicated in Figure 22.
with the universal stage. Calcite is uniaxial with its optic axis parallel to the C crystallographic axis. With the universal stage, a thin section can be oriented in any position. Calcite fibers were oriented with the Universal stage so that the optic axis of a fiber was parallel to the axis of the microscope. Procedures followed when operating the universal stage are fully explained in Emmons (1943) and Phillips (1971). The orientation of the cut section was determined with the use of a contact goniometer and stereographic constructions from the known orientation of one plane of the hand sample. It was concluded that the C-axes of these fibrous crystals are parallel to fiber length.

After the crystal has been rotated into its desired position, the pointers on the scales are read. The position of the optic axis can then be plotted on a stereonet. The mean C-axis orientation was determined from the plotted points. If more than one area was prominent on the stereonet, this indicated that the thin section cut through more than one given fiber increment in a vein and thus recorded a change in fiber orientation. The fiber orientations for two samples from Locality A at Ankerfjella, two samples from Locality C at Holmesletfjella, and two samples from Locality E at Bulltinden were determined. The C-axis orientations determined in this method agreed well with fiber orientations obtained from the incremental strain analysis. The results from this part of the analysis are
also plotted at the end of Appendix A.

From the incremental extension data, successive cumulative strain states can be calculated with matrix multiplication. The progressive widening of the veins and lack of folded fibers allows the incremental strain recorded by a fiber segment to be represented by a deformation matrix ($D_i$, Equation 1, Appendix B). The multiplication of two or more successive matrices (Equation 2, Appendix B) gives the cumulative strain $D(ci)$ based on the increments defined by those matrices. This cumulative strain does not incorporate the total number of fiber increments for a set of data:

$$D(ci) = D_{n-1} \times D_{n-2} \times D_1.$$

By successively multiplying the deformation matrices associated with all of the incremental strains for a set of data gives the deformation matrix ($D(c)$) for the total, cumulative strain recorded by the entire length of the fibers:

$$D(c) = D_n \times D_{n-1} \times D_{n-2} \times \ldots \times D_1.$$

The components of the matrix $D(c)$ can be used to calculate the values of the principal strains ($1+e_1$) and ($1+e_2$) (Equation 3, Appendix B). The orientation of the final strain ellipse can also be determined (Equation 4, Appendix B) from the components of the final $D(c)$ matrix for each
locality.

The calculated principal strains for the select samples of Figures 44 through 47 are given in Table 2 and those principal strains based on the summary diagram of Figure 48 are presented in Table 3. Each line of data (values for A, B, C, D, \(1+e_1\), and \(1+e_2\)) represents the cumulative strain recorded in the fibers up to and including that segment. The values of \(1+e_1\) and \(1+e_2\) in the last line for each data set are the total cumulative principal strains calculated for the entire length of the fibers for that set. Included in Table 4 are the X directions of the cumulative strain ellipses and the angles between the first and latest fiber segments for each data set in Figure 48.

5.3.4 Discussion of Summary Diagram

At locality A, the first-formed fiber increment, with a trend of 280 and a plunge of 10 degrees, has an average incremental extension value of 3.97 (Fig. 48, A). The latest-formed fiber segment has a plunge of 25 degrees toward 240. The fibers have been reoriented from their original position and show a variation in orientation through an angle of 40 degrees in the plane of cleavage. The incremental extension values decrease rapidly between the first and subsequent fiber segments. At locality B, the first-formed fibers are also oriented toward the northwest and the latest-formed fiber segment is oriented toward the southwest. Another set of analyzed fibers indicates fiber
<table>
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<th>Trend and Plunge of Fiber Segment</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>(1+e₁)</th>
<th>(1+e₂)</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
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<td>0.0000</td>
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</tr>
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orientations to the northeast (Fig. 48, B). At locality B, there are two distinct cleavage orientations and the fiber orientations appear to be symmetric; one set has a maximum value plunging 11 degrees to the west and the other 12 degrees to the east. In both cases, the third-formed fiber increment shows a relative increase in the amount of extension and both areas indicate the angle between the first and latest increments to be 30 degrees. These fibers may have attained their present orientation during the formation of the gentle synform at central Ankerfjella.

The largest average incremental extension values on the south side of the fjord are slightly less than those from Ankerfjella. At locality C on Holmesletfjella, the first-formed fiber increment is oriented towards 280 with a plunge of 14 degrees and has an incremental strain value of 1.59. The latest-formed fiber segments in this area are oriented toward 220 with a plunge of 30 degrees. At Locality D, the fiber orientations are all toward the southwest. When compared to locality C, the first-formed fiber segments here have a greater average incremental extension value of 3.15 whereas the latest-formed fiber segment has a lesser average incremental extension value of 0.0029. At Holmesletfjella, there is also a large decrease in extension values between the first and subsequent fiber segments. The angle between the first-formed and latest-formed fiber segments at C is 60 degrees and at D it is 40 degrees.
At localities E and F at Bulltinden, the first-formed fibers have average incremental extension values of 3.44 and 2.2, respectively. Both of these fiber segments are oriented toward the east with plunges of 15 degrees at E and 20 degrees at F. The latest-formed fiber segments at Bulltinden are also oriented toward the southwest. The angle between the first and latest fiber segments at Bulltinden ranges from 40 to 60 degrees. The initial average incremental extension values at Ankerfjella were 3.97 and 4.13 and the average initial incremental extension values at Bulltinden and Holmesletfjella were slightly less, averaging 1.59 to 3.44.

For each locality, the total displacement across the measured veins, which average 1.0 to 1.5 cm in width, can be compared. The orientation of the final cumulative strain ellipses are similar. The calculation of the cumulative strain values are dominated by the large, initial fiber increment (Tables 2 and 3). These ellipses however record different amounts of final cumulative strain. In localities B, D, E, and F, plane strain is measured. In areas of greater fiber rotation (localities A and C) the maximum incremental extension direction associated with the latest-formed fiber is at a high angle to the X direction of the cumulative strain ellipse. In these two cases, a significant amount of extension has occurred in the Y direction.

At Ankerfjella, the cumulative strains \((1+e_1, 1+e_2)\) for
Localities A and B are (6.20, 1.10) and (5.81, 1.01), respectively. These are the largest calculated cumulative strains of all the sampled areas. The second set of cumulative strains for Locality B are (6.04, 1.03) and these are similar to the other values for the Ankerfjella localities.

At Locality C, the cumulative strains are (3.03, 1.19) and at Locality D the values are (4.56, 1.01). The long axes of the cumulative strain ellipses are oriented toward 274 and 258, respectively. At Bulltinden, the cumulative strains for localities E and F are (4.99, 1.04) and (3.44, 1.01) respectively. Both the long axes of the cumulative strain ellipses and the first-formed fiber increments at these localities are oriented toward the east. Locality C has the lowest cumulative strain values and also had lower local strains when compared to locality A.
CHAPTER SIX

TECTONIC SIGNIFICANCE

6.1 Structural Relationships

For the analyzed samples, the latest-formed fibers plunge to the west-southwest and the first-formed fibers are parallel to local fold axes (Fig. 49). Overall, the analyzed fibers indicate a consistent rotation pattern and show no great variation in incremental extension orientations across the Bullbreen Group. Most of the fiber segments are oriented toward the west-southwest and a small number of fiber segments are oriented toward the east.

The sigmoidal fiber patterns indicate a changing principal incremental strain direction. The sense of rotation of this change depends on the frame of reference from which the deformation is viewed. The two simplest possibilities are: (1) a stationary rock mass within a rotating strain regime, or (2) a rotating rock mass within a stationary strain regime. In order to compare the deformation to a model, a fixed frame of reference is needed. Either the rock mass or the extensional strains can be considered to be stationary.

After crack initiation, the tectonic extension and compression orientations may vary. The principal strain axes may rotate as the fracture propagates and fills with fibrous material. The newly-formed fiber segments align themselves parallel to these new strain axes. For this
Figure 49. Map of the western end of St. Jonsfjorden showing the principal sampled exposures of the Bullbreen Group. The equal-angle stereographic plots indicate fold axis orientations and directional changes in fiber orientation. The arrows indicate the regional sense of fiber rotation. The localities are as indicated in Figure 22.
deformation style, rotation of strain axes within a non-rotating rock mass, these fibers record a sinistral sense of rotation.

However, the strain axes may retain a consistent orientation while the wall rock and first-formed fiber crystals rotate as the fractures widen. Newly-formed fibers continue to parallel the extension direction and also grow at an angle to earlier-formed fibers. For this deformation style, rotation of the rock mass within consistently oriented strain axes, the sigmoidal fibers indicate a dextral sense of rotation.

6.2 Strain Modelling

A tectonic explanation for the observed features must incorporate a dextral rotation of the rock mass, sub-parallelism of the fold axes and maximum extension directions, and northeastward thrust movements. A model capable of properly relating these elements is one involving transpression. Transpression has been defined (Harland, 1971; Sanderson and Marchini, 1984) as a combination of deformation processes acting within a shear zone. It involves horizontal shortening across a transcurrent shear zone with vertical lengthening along the shear plane (Fig. 50).

Transpression is thought to occur within the narrower, discrete zones between compressive plate boundaries. Structural variability is limited and rocks are elongated
Figure 50. Simplified sketch of a block diagram showing the directions in which deformation processes occur during transpression. The centre block, originally a unit cube, is transformed into its present state by shortening parallel to the B axis and shear parallel to the A axis. The volume of the middle block is conserved by lengthening parallel to the C axis (after Sanderson and Marchini, 1984).

Superimposed on the top of the middle block is a sketch of the western end of St. Jonsfjorden showing the Bullbreen Group outcrop pattern and the shear zone boundaries. This area of the diagram is enlarged in Figure 51.
parallel to fold axes. In adjacent areas where the plates are wider apart, more diverse and complex structures may develop (Harland, 1971). Because the continental lithosphere is a rising rather than a downgoing slab, thrust sheet stacking, rather than subduction, conserves volume in the zone. The surface expressions are primarily in a deformed, narrow zone of sedimentary rocks.

Within these zones, characteristic structures are en echelon folds and extreme clast elongation in deformed conglomerates. Folds which develop during the process are rotated into a position whereby fold axes trend sub-parallel to the shear zone. Other evidence for transpression are the presence of curved faults in plan view (see Fig. 4) and the absence of metamorphism and ophiolites (Lowell, 1972).

This process could be responsible for the development of structures in the St. Jonsfjorden area. Strongly-developed cleavage and clast elongation parallel to the fold axes (Fig. 33) is evident in the Holmesletfjella conglomerates. Clasts in the tillites of the lower rock package are elongated up to five times parallel to the fold axes (Harland, 1971). The Bullbreen Group is a thrust sheet of narrow extent and exhibits sub-greenschist metamorphism. En echelon folds are found along the west coast of Spitsbergen (Lowell, 1972).

A problem in using a transpression deformation event to explain Bullbreen Group structures is that vertical cleavage plane development is predicted as compression is
assumed to be acting in a horizontal direction (Sanderson and Marchini, 1984). Cleavage in the Bullbreen Group has a shallow to moderate dip. A modified form of transpression which incorporates thrust shear into the transcurrent shear deformation has been developed by Ratliff (1985). An added constraint to this transpression model is an excess loading in the vertical direction as a result of folding and thrusting. This modified model was developed, in part, as a result of the preliminary analysis of the Bullbreen Group syntectonic calcite fibers which indicated a rotational strain history.

The modified transpression model developed by Ratliff predicts, for a given set of thrust and transverse shear parameters, the deformation paths of the principal strain axes. These principal strain paths are produced by the determination of a number of successive incremental strain directions. These increments are based on components of Incremental thrust (\(\delta T\)) and incremental shear (\(\delta S\)) which are incorporated into coordinate transformation equations defining the deformation path (Sanderson and Marchini, 1984). These equations are used to describe the translation of points in three-dimensional space.

As shown by the distribution of Bullbreen Group outcrops in Figure 14, the areal distribution of this group is of limited extent. The boundaries of the postulated transpression zone are based on this outcrop pattern (Fig. 51). Thrusting, assumed to be perpendicular to the regional
Figure 51. Map of western end of St. Jonsfjorden showing postulated shear zone boundaries. Solid arrows indicate dextral sense of shear, outlined arrows indicate direction of thrusting. Rotation of fibers indicated in equal-angle stereographic plots.
fold axis, is to the north and northeast. A southward-dipping cleavage also supports this thrusting direction, as compression is assumed to be acting in a southwest-northeast direction. Compaction and volume loss is assumed to occur in a vertical direction. The three-dimensional reference coordinate system for the displacement matrices is based on these relative movement directions. A is parallel to the zone margin and parallel to the transverse shear direction. B is perpendicular to the inferred zone boundaries and is parallel to the thrust shear direction. C is parallel to the compaction and vertical loading direction. These directions are consistent with those of Figure 50.

The modeled strain effects are compaction and volume loss, transverse shear, and thrust shear. Each increment of deformation was determined from matrix multiplication in the following way:

\[
\begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1+\Delta
\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & \gamma_T \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & \gamma_S & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

\text{deformation increment} = (DM_j)

\text{compaction} \quad \text{thrust} \quad \text{transverse shear}

\text{shear}

Since the non-diagonal matrix elements above are small, the model results do not differ greatly when the imposed strain sequence, the order in which the matrices are multiplied, is changed.
\[
\mathbf{Dm_1} = [V][S][T] = [S][V][T]
\]

Using the assumption of a constant incremental strain rate, the deformation matrix at the end of \( n \) increments is:

\[
\mathbf{D} = \mathbf{DMn} \times \mathbf{DMn-1} \times \mathbf{DMn-2} \times \ldots \times \mathbf{DM_1}
\]

The multiplication of \( \mathbf{D} \) by the transposed matrix of \( \mathbf{D} \) results in a final deformation matrix \( \mathbf{DD^T} \). Eigenvalues and eigenvectors which define the orientation and magnitudes of the principal cumulative strains can be obtained from this \( \mathbf{DD^T} \) matrix. The eigenvectors, which represent the principal strain directions, change in orientation as progressive deformation occurs. Figure 52 shows the changing principal strain paths predicted for the three given sets of shear parameters. Next to each plot are the values of \( \gamma_T \) and \( \gamma_S \) used in the matrices. These plots do not represent deformation paths.

6.3 Discussion of Transpression Model

This tectonic model explains well, using the effects of thrust shear (\( \gamma_T \)) and transcurrent shear (\( \gamma_S \)), the data and observations in the field area and combines this information into a logical pattern of deformation. Equal amounts of transverse and thrust shear appear to fit most closely the observed field data (second stereonet of Fig. 52). Poles to the cleavage in the Bullbreen Group and the XY plane of the
Figure 52. Equal-angle stereographic plots showing deformation paths of principal strain directions as predicted by computerized transpression model (after Ratliff, 1985).
predicted finite strain ellipsoids are sub-parallel when these shear components of the model are equal. The predicted maximum finite extension directions are estimated to be oriented towards the west-northwest, very close in orientation to what is indicated by the calcite fibers. Both of these features are shown in Figure 53. In addition, an X-Y ratio of 1.7 and an X-Z ratio of 2.3 also obtained from these same components are believed to be minimum strain estimates (Ratliff, personal communication). Vertical shortening is predicted to range from 10 to 25 percent.

The change in the orientations of the calcite fibers in the Bullbreen Group extension veins is explained by this model. As the boundaries undergo dextral shear and thrusting, the maximum incremental extension direction in the zone has an orientation which is at 45 degrees to the zone boundary (Fig. 54, A). Veins will begin to form and widen parallel to this extension direction. Fibers forming in these veins will parallel the initial extension direction. As the shear zone continues to develop, the initially formed fibers will be rotated out of their initial orientation. Veins continue to open and new fibers will form parallel to the incremental maximum extension direction (Fig. 54, C and D). If both wall rock and vein material rotate while the incremental extension direction remains relatively constant, a dextral rotational sense is preserved in the fibers (Fig. 54). As long as conditions for vein propagation and fiber growth are present, the fibers
Figure 53. Equal-angle stereographic projection showing maximum and minimum extension directions predicted by transpression model incorporating equal amounts of transverse shear and thrust shear (Ratliff, personal communication).
Figure 54. Sketch showing sigmoidal fiber development within a dextral shear zone. A. The initiation of strike-slip motion causes extension to develop at 45 degrees to zone boundary. Fractures open and the first-formed fibers grow parallel to this X direction. B. As shear continues, the rock matrix (indicated by shaded semi-circles) and first-formed fibers are rotated and the fracture widens. C. New fiber increments (indicated by $e_i$ notation) are added at vein-wall contacts parallel to the X direction. D. Additional fiber lengths formed during crack-seal episodes within a rotating rock mass result in the development of sigmoidal fibers, as observed in the field area.
continue to grow and record extension directions in the rock. Once formed, the veins may be rotated and tilted into a range of new orientations as the rocks are folded and thrusted.

Although pebble long axis alignment does not in itself unequivocally demonstrate that fold axes are parallel to the extensional direction (Ratliff, 1985), the orientations of both the veins and fibers, as well as other field and laboratory data (Fig. 33) indicate true extension parallel to the fold axes has occurred. The traverses drawn in the finite strain analysis (Figs. 37 and 39) are for the most part parallel to the directions in which the veins have opened. This data also supports the existence of an significant extension parallel to the local fold axes. Hobbs et al. (1976) discussed further the mechanisms by which extensional strains and fold axes orientations can be parallel or sub-parallel.

6.4 Fold Formation

Fold development in shear zones has been discussed by earlier workers (Harland, 1971; Sanderson, 1973). Fold formation equations by Biot (1961) predict explosive fold initiation followed by later tightening of fold hinge regions. During the transpression process, an initial build-up of pre-folding stresses may occur. This stored energy can be released and result in the formation of the folds, at 45 degrees to the strike-slip zone boundary (Fig.
The extensional direction existing at the time of vein formation was consistent; in a given sampled area, the central fiber segments of all veins from that area have the same general orientation. These central fiber segments are also parallel to fold axes (Fig. 56). During fracture initiation, a large opening can occur over a short period of time during which a large amount of fiber growth may occur. Fold formation may have been contemporaneous with fracture initiation and the formation of the first fiber segments.

This initial period of fold and fracture initiation during the D2 deformation phase was followed by a period during which the veins experienced a reduced amount of fracturing and widening. Veins with straight fibers did not continue to open after the initial high strains in the rocks were recorded by the longest fiber segments. The veins with sigmoidal fibers did, however, continue to open and record the incremental strain directions.

Dextral rotation is assumed to be constant throughout this part of the D2 event. The length of time over which a fiber grows is not known; the growth rates of fibers depend on the deformation conditions and the amount of soluble material present.

Part of the deformation affecting the west coast of Spitsbergen has been related to the opening of the Norwegian and Greenland seas. The northward movement of Greenland and eastward movement of Svalbard was accomplished in part by
Figure 55. Four sequential sketches explaining the development of folds within a zone undergoing dextral transpression. A. Initiation of strike-slip motion with subsequent maximum extension direction (X) oriented at 45 degrees to the shear zone margins. B. Thrust and transverse shear components cause folds to develop and fold axes to be parallel to the extension direction. C. Continued transpression causes folds to tighten and fold axes to rotate in a dextral sense (indicated by dashed and solid lines at top of sketches). D. Inferred relationships between fold axes orientations and postulated shear zone boundaries in the field area (modified after Harland, 1971).
Figure 56. Sketch of a single-layer fold in which calcite extension veins (shaded areas) have developed. The fractures have opened in a direction, labeled (X) and indicated by arrows, parallel to the fold axis. Calcite fibers found in the veins are parallel to this X direction (after Fyfe et al., 1978).
translations along the Spitsbergen Fracture Zone (Fig. 57). The structures present in the rocks of the Spitsbergen west coast record patterns of dextral movement along oblique strike-slip faults (Harland, 1971; Lowell, 1972).

It has been stated earlier (Section 2.3) that the Western Complex of Spitsbergen has been subjected to three major deformational events during the Phanerozoic. The latter two events, believed to have taken place in late Caledonian and Tertiary time, show evidence of similar deformation styles; horizontal transcurrent movement along occasionally compressive margins. Sinistral movements during the late Devonian (Fig. 4) have been suggested previously by Harland (1971) and Harland and Wright (1979). The study of the veins has indicated that dextral rotation must also have occurred at this time. Dextral transpression is also believed to have occurred during the Tertiary deformation event in west Spitsbergen (Fig. 57) (Harland and Gayer, 1972; Harland, 1978; Kowallis and Craddock, 1984).
Figure 57. Sketch maps of the northern Atlantic and Arctic ocean regions. A. Sketch of a pre-Tertiary reconstruction showing the position of Svalbard and continental plate boundaries. B. Sketch showing the present position of Svalbard, the ocean ridges, and the Spitsbergen Fracture Zone (after Lowell, 1972).
CHAPTER SEVEN

SUMMARY

This study was undertaken in an attempt to describe in
greater detail some of the structures present in the St.
Jonsfjorden area and to try to relate these structures to a
regional, geologic setting. The basis of this study were
the calcite extension veins and the sigmoidal fibers
contained within these veins found in the Bullbreen Group.

Local finite strains were determined from groups of
veins and incremental and cumulative strains were determined
from individual veins. The sigmoidal fibers showing the
greatest range of fiber orientations were used to calculate
the magnitude and direction of incremental extensions.

Earlier workers in the St. Jonsfjorden area frequently
referred to extensions parallel to fold axes. This study
gives a quantitative measure of the amount of local
extension that has occurred parallel to fold axes. The
general direction in which these veins have opened is
parallel to local fold axes. The finite strain analysis
performed using the outcrop pattern of these veins gave
amounts of measured finite extension ranging from 10% to
nearly 100%. At Ankerfjella, the measured finite strains
averaged 1.35 and at Holmesletfjella the strains averaged
1.20.

The analysis of the fibers in the veins also produced
very consistent results. The first fiber segment was the
largest and the subsequent segments were progressively smaller. The directions of the first-formed fiber segments are parallel to local fold axes and the latest-formed fiber segments are oriented toward the southwest. Incremental extension values decrease greatly between the first and subsequent fiber segments. The general sense of rotation that has occurred during the formation of these fibers is uniform, 30 to 60 degrees. The averaged incremental extensions based on an initial wall rock segment of 0.5 mm recorded by the first-formed fiber segments range from 1.59 to 4.13.

Cumulative strain ellipse magnitudes and orientations were calculated from the incremental strains. All cumulative strain ellipses have their long axes oriented sub-parallel to local fold axes.

Part of the Bullbreen Group's strain history is recorded by these sigmoidal fiber growths. The fibers provide substantial evidence for the existence of a rotational event during their formation. These fibers, along with other major structural features found in the field area can now be explained well by a dextral transpression event.

To date, the ages of igneous and sedimentary rocks found in the St. Jonsfjorden area are not well known. A geochronological study of various rocks would prove to be beneficial to the reconstruction of the area's deformational history. This information could provide definitive time constraints on the discussed deformation events.
APPENDIX A

The equal-angle stereographic plots on the following pages show, for each sample analysed, the incremental changes in fiber orientation and corresponding calculated incremental extensions for each fiber segment. For each of these plots, the following legend is used:

- First-formed fiber segments
- Latest-formed fiber segments
- Sense of fiber rotation

The final plots included here show the C-axis orientations of the calcite fibers in selected samples. Each point on these projections represents the average orientation of three to five individual fibers.
Ankerfjella
Locality A
Holmesletfjella
Locality C
Holmesletfjella
Locality C

D59

D62

210

260

270

240

230

270

280

220
Holmesletfjella
Locality C
Holmesletfjella
Locality C

D72

280
260
240
210

D73

280
260
250

Holmesletfjella
Locality D
Bulltinden
Locality E

D82

D85
Calcite Fiber Orientations
C Crystallographic Axes

Ankerfjella
Locality A
APPENDIX B

Incremental Strain Matrix - In a system where extension in the Y direction is close to zero, each incremental strain state can be represented by a displacement matrix:

Equation 1
\[
\begin{bmatrix}
  a_i & b_i \\
  c_i & d_i
\end{bmatrix} = \begin{bmatrix}
  (1 + e_i) \cos^2 \Theta + \sin^2 \Theta & e_i \cdot \sin \Theta \cdot \cos \Theta \\
  e_i \cdot \sin \Theta \cdot \cos \Theta & \cos^2 \Theta + (1 + e_i) \sin^2 \Theta
\end{bmatrix}
\]

displacement matrix

(Ramsay and Huber, 1983, p. 253)

The components of the incremental displacement matrix are defined by the incremental extension values. $\Theta$ is the angle between a reference direction and the fiber segments under consideration.

Superposition of Two Displacements - The position of a point after displacement can be described with a transformation equation. The total translation of a point from an initial state through two successive displacements is given by:

Equation 2
\[
\begin{bmatrix}
  a_2 & b_2 \\
  c_2 & d_2
\end{bmatrix} \times \begin{bmatrix}
  a_1 & b_1 \\
  c_1 & d_1
\end{bmatrix} = \begin{bmatrix}
  a_2 a_1 + b_2 c_1 & a_2 b_1 + b_2 d_1 \\
  c_2 a_1 + d_2 c_1 & c_2 b_1 + d_2 d_1
\end{bmatrix}
= \begin{bmatrix}
  A & B \\
  C & D
\end{bmatrix}
\]

second displacement matrix \times first displacement matrix = final displacement matrix

(Ramsay and Huber, 1983, p. 292)
Calculation of Principal Strains - After a series of successive displacements, the principal strain values can be obtained from the final displacement matrix in the following way:

Equation 3

\[(1+e_1)^2 \text{ or } (1+e_2)^2 = \]

\[
\frac{A^2 + B^2 + C^2 + D^2}{2} \pm \frac{1}{2} \left( (A^2 - B^2 + C^2 - D^2)^2 + 4(AB + CD)^2 \right)^{1/2}
\]

(Ramsay and Huber, 1983, p. 287)

\[(1+e_1)^2\] can be obtained by adding both halves of equation 2.

\[(1+e_2)^2\] can be obtained by subtracting the second half of equation 2 from the first half.

Directions of the principal strains after deformation - The orientation of the axes of the cumulative strain ellipse axes can be calculated from the following:

Equation 4:

\[
\tan 2\Theta = \frac{2(AC + BD)}{A^2 + B^2 - C^2 - D^2}
\]

(Ramsay and Huber, 1983, p. 286)

The value of \(\Theta\) is the angle between the reference direction and the long axis of the cumulative strain ellipse.
REFERENCES


VITA AUCTORIS

Matthew Edward Dodt
7629 Pinehurst
Dearborn, Michigan 48126

SUMMARY OF BACKGROUND

September, 1984 to January, 1986 - Graduate Student Teaching Assistant - University of Windsor, Windsor, Ontario, Canada. Preparation and explanation of introductory laboratory exercises, Explanation of Third-year Structural Geology laboratory exercises.
September, 1983 to April, 1984 - Teaching Assistant - Wayne State University, Detroit, Michigan. Preparation of laboratory exercises for structural geology and introductory geology.

EXPERIENCE

Computer Programming - Involved in the design, structure, and completion of programs dealing with geological and geotechnical data. Experience in FORTRAN, BASIC, DOS systems, and word processing.
Field Assistant - 1983 Wayne State University Spitsbergen Expedition. Participated in several structural studies and contributed to a revised geologic map of the study area.

MEMBERSHIPS

Phi Beta Kappa
Golden Key National Honor Society

AWARDS

University of Windsor Postgraduate Scholarship 1984-1986
Wayne State University Merit Scholarship 1980-1984
National Association of Geology Teachers Summer Field Course Award 1983
Wayne State University Geology Department Faculty Merit Award 1982

PERSONAL

U.S. citizen, married, excellent health