

STRUCTURAL GEOLOGY OF PALEOZOIC ROCKS,  
LAKE MASSAWIPPI AREA,  
EASTERN TOWNSHIPS,  
QUEBEC

by

Stanley Daniel Robinson

A thesis

submitted in partial fulfillment of the requirements

for the degree of

MASTER OF SCIENCE

in the

Department of Geology

University of Ottawa

February 1974

ABSTRACT

Polyphase fold structures in Cambro-Ordovician meta-sedimentary and metavolcanic rocks of the Ascot Formation in the southern part of the Stoke Mountain complex are compared with those to the east in Siluro-Devonian limestone, argillite and sandstone of the St. Francis Group. With the aid of previous structural studies of rocks further west and north, a revised deformational history is proposed.

The oldest structures recognized within the Ascot Formation are small isoclinal folds ( $F_1$ ) and an axial-plane schistosity with aligned sericite and chlorite. As previously shown (St-Julien and Lamarche, 1965), fragments of the schist and associated albite granite are present in conglomerates in structural continuity with Middle Ordovician (Trenton) rocks. Hence the folding with growth of fabric-forming minerals was pre-Trenton and possibly an early expression of the Taconic orogeny.

Second phase tight folds ( $F_2$ ) in bedding and schistosity in the Ascot Formation may include major folds that partly determine the outcrop pattern. Small scale  $F_2$  folds plunge steeply to moderately northeast nearly parallel to isoclinal first folds ( $FF_1$ ) in adjacent rocks of the St. Francis Group. Furthermore, steep axial-plane foliations appear to continue across the boundary of the Ascot Formation into the younger rocks. These relationships suggest that  $F_2$  and  $FF_1$  folds are coeval. Refolding during the mid-Devonian Acadian orogeny is implied.

Third phase folds in the Ascot Formation are generally open with axial-plane crenulation cleavages dipping moderately northwest. Folds of similar style and orientation are present in the St. Francis Group, and in the Middle Ordovician rocks to the west.

The tectonic setting and style of successive folds suggest that in the early Ordovician there was a period of isoclinal recumbent folding and low-grade metamorphism perhaps accompanying the emplacement of Taconic nappes. After initial subhorizontal shortening during the much later Acadian orogeny, there was limited subvertical shortening, possibly in response to crustal extension.

TABLE OF CONTENTS

	page
INTRODUCTION -----	1
Location -----	1
Relief, Accessibility and Outcrop Type -----	1
Geologic Setting -----	3
Previous Work -----	6
Stratigraphic Relations -----	6
Structural Relations -----	6
Faults -----	15
Purpose and Scope of the Present Study -----	16
Field Procedure -----	17
Acknowledgements -----	17

II

STRATIGRAPHY -----	19
Introduction -----	19
Cambrian to Lower Ordovician Rocks -----	22
Ascot Formation -----	22
Acid Volcanics (map unit A1) -----	22
Siltstone, Sandstone, Tuffaceous (?) Rocks and Chert (map unit A2) -----	23
Graphitic Phyllites (map unit A3) -----	24
Sericitic (Chlorite) Schist (map unit A4) -----	24
Stratigraphic Relations of the Ascot Formation with the Magog and St. Francis Groups -----	25
Ultramafic Rocks, (map unit I1) -----	26
Albite Granite (map unit I2) -----	27

	page
Middle and Upper Ordovician Rocks - - - - -	28
Magog Group - - - - -	28
Beauceville Formation (map unit M1) - - - - -	28
Sherbrooke and East Branch Pond Formations -	28
<hr/>	
Middle Silurian to Devonian Rocks: St. Francis Group	29
Northfield Formation (Lower St. Francis Group) (map unit F1) - - - - -	29
Waits River Formation (Lower St. Francis Group) -	30
Ayer's Cliff Member (map unit F2) - - - - -	30
Barton River Member (map unit F3) - - - - -	31
Gile Mountain Formation (Upper St. Francis Group) - - - - -	34
Westmore Member (map unit F4) - - - - -	34
Middle Silurian to Devonian Rocks: Glenbrooke Group and Lake Aylmer Formation - - - - -	36
Middle or Upper Devonian Rocks - - - - -	37
Granite (map unit I3) - - - - -	37
Upper Devonian (?) Rocks - - - - -	39
Diorite (map unit I4) - - - - -	39
Cretaceous (?) Rocks - - - - -	39
Dykes - - - - -	39

III

STRUCTURES - - - - -	40
Introduction - - - - -	40
Ascot Formation - - - - -	40
D <sub>1</sub> Deformation - - - - -	40
F <sub>1</sub> Folds - - - - -	40
S <sub>1</sub> Foliation - - - - -	45

	page
L <sub>1</sub> Lineations	46
D <sub>2</sub> Deformation	47
F <sub>2</sub> Folds	47
S <sub>2</sub> Cleavage	47
L <sub>2</sub> Lineations	50
D <sub>3</sub> Deformation	50
F <sub>3</sub> Folds	50
S <sub>3</sub> Cleavage	52
L <sub>3</sub> Lineations	52
Metamorphism	53
St. Francis Group	54
DD <sub>1</sub> Deformation	54
FF <sub>1</sub> Folds	54
SS <sub>1</sub> Cleavage	58
LL <sub>1</sub> Lineations	61
DD <sub>2</sub> Deformation	63
FF <sub>2</sub> Folds	63
SS <sub>2</sub> Cleavage	63
LL <sub>2</sub> Lineations	65
DD <sub>3</sub> Deformation	66
SS <sub>3</sub> Cleavage	66
LL <sub>3</sub> Lineations	66
Metamorphism	66
Magog Group	67
Beauceville and Sherbrooke Formations	67
Glenbrooke Group	70
Relationship Between Small Scale and Major Structures	70

	page
Stoke Mountain Complex: Ascot Formation - - - -	70
St. Victor Synclinorium: Magog Group - - - -	74
Connecticut Valley - Gaspé Synclinorium: St. Francis Group - - - - -	74
Correlation of Structures and Age of the Deformation	77
Tectonic Deformational Phase III - - - - -	79
Tectonic Deformational Phase II - - - - -	80
Tectonic Deformational Phase I - - - - -	82
IV	
SYNTHESIS - - - - -	83
Tectonic History - - - - -	83
Tectonic Evolution in Relation to Plate Tectonics -	86
Introduction - - - - -	86
Facies Relations - - - - -	89
Structural Succession - - - - -	90
Problems and Suggestions for Future Work - - - -	91
REFERENCES - - - - -	93
APPENDIX I FOLD CLASSIFICATION - - - - -	104
APPENDIX II EQUAL AREA NET PROJECTIONS - - - - -	107
APPENDIX III ECONOMIC GEOLOGY - - - - -	114
PLATES - - - - -	118

LIST OF FIGURES

	page
1 A) Geographic map, Lake Massawippi area, B) Location of study area - - - - -	2
2 Geologic map of the Eastern Townships and adjoining areas showing major tectonic units and structures - - -	4
3 Map of fossil localities in the Eastern Townships and in northern Vermont and Maine - - - - -	10
4 Map of main rock units and major structures, Lake Massawippi area and vicinity - - - - -	12
5 Stratigraphic map of the Lake Massawippi area - - - - -	21
6 Structural map and cross sections of the Lake Massawippi area - - - - -	in pocket
7 Map of the Lake Massawippi area with equal area net projections and modal average orientations of lineations and cleavages - - - - -	in pocket
8 Map of modal orientations of structures; Lake Massawippi, Magog and Sherbrooke areas - - - - -	41
9 Cross sections of the study area and surrounding district - - - - -	42
10 $F_1$ fold profile - - - - -	44
11a $F_2$ fold profiles - - - - -	48
11b $F_2$ fold profiles - - - - -	49
12 $F_3$ crenulations and slip cleavage - - - - -	51
13 $FF_1$ fold profile - - - - -	56
14 $FF_1$ and $FF_2$ fold profiles - - - - -	57
15 Tectonic "boulders" in the $SS_1$ plane - - - - -	59
16 Graph comparing steepness of $FF_1$ fold structures in the St. Francis Group with distance southeast of the Stoke Mountain complex - - - - -	62
17 $FF_2$ fold profiles - - - - -	64
18 Diagrammatic sketch of possible large scale folds suggested by changes in dip of $S_0$ and $S_1$ in the Ascot Formation - - - - -	73

	page
19 Interpretations of $FF_1$ folds and enveloping surface	76
20 Pictorial summary of the geological events in the Lake Massawippi area - - - - -	84
21 Experimentally formed kink band - - - - -	87
22 Fundamental types of fold classes - - - - -	104
23 Equal area nets, computer plots - - - - -	110
24 Hand contoured equal area net - - - - -	111
25 Compilation equal area nets - - - - -	112

LIST OF TABLES

	page
1 Stratigraphic Relations of the Quebec Group: Historical Summary - - - - -	7
2 Stratigraphic Relations of the "Gaspé Limestones": Historical Summary - - - - -	8
2 Continued - - - - -	9
3 Siluro-Devonian Correlatives in the Connecticut Valley - Gaspé Synclinorium - - - - -	11
4 Table of Formations - - - - -	20
5 Characteristics of Structures: Ascot Formation (Cambrian or Lower Ordovician) - - - - -	43
6 Characteristics of Structures: St. Francis Group (Devonian and Upper and Middle Silurian) - - - - -	55
7 Characteristics of Structures: Magog Group; Beauceville and Sherbrooke Formations (Middle to Upper Ordovician) - - - - -	69
8 Characteristics of Structures: Glenbrooke Group (Upper Silurian) - - - - -	71
9 Correlation of Minor Structures and Age of Deformation - - - - -	78
10 Fold Classification: Ascot Formation - - - - -	105
11 Fold Classification: St. Francis Group - - - - -	106

## INTRODUCTION

### Location

The study area covers approximately 354 square miles (906 square km) in the Eastern Townships, Québec, about 80 miles (128 km) southeast of Montreal (Fig. 1).

The southern boundary is the International Border extending from Longitude  $72^{\circ} 15' W$  to Longitude  $71^{\circ} 59' W$ . The northern boundary is Latitude  $45^{\circ} 20' N$  extending from Longitude  $72^{\circ} 05' W$  to Longitude  $71^{\circ} 39' W$ .

The area includes Hatley, as well as a part of Magog, Stanstead and Barnston Townships in Stanstead County, and a portion of Orford and Ascot Townships in Sherbrooke County as well as a part of Eaton, Compton and Clifton Townships in Compton County. It is covered by parts of Coaticook, Sherbrooke, Orford and Memphremagog topographic sheets of the Canadian National Topographic 1:50,000 Series (21E/4, 21E/5, 31H/8 and 31H/E1 respectively).

### Relief, Accessibility and Outcrop Type

Gently rolling hills occupy most of the area, however there are also large tracts of relatively flat land. The elevation varies from about 500 feet (152 m) at the lowest

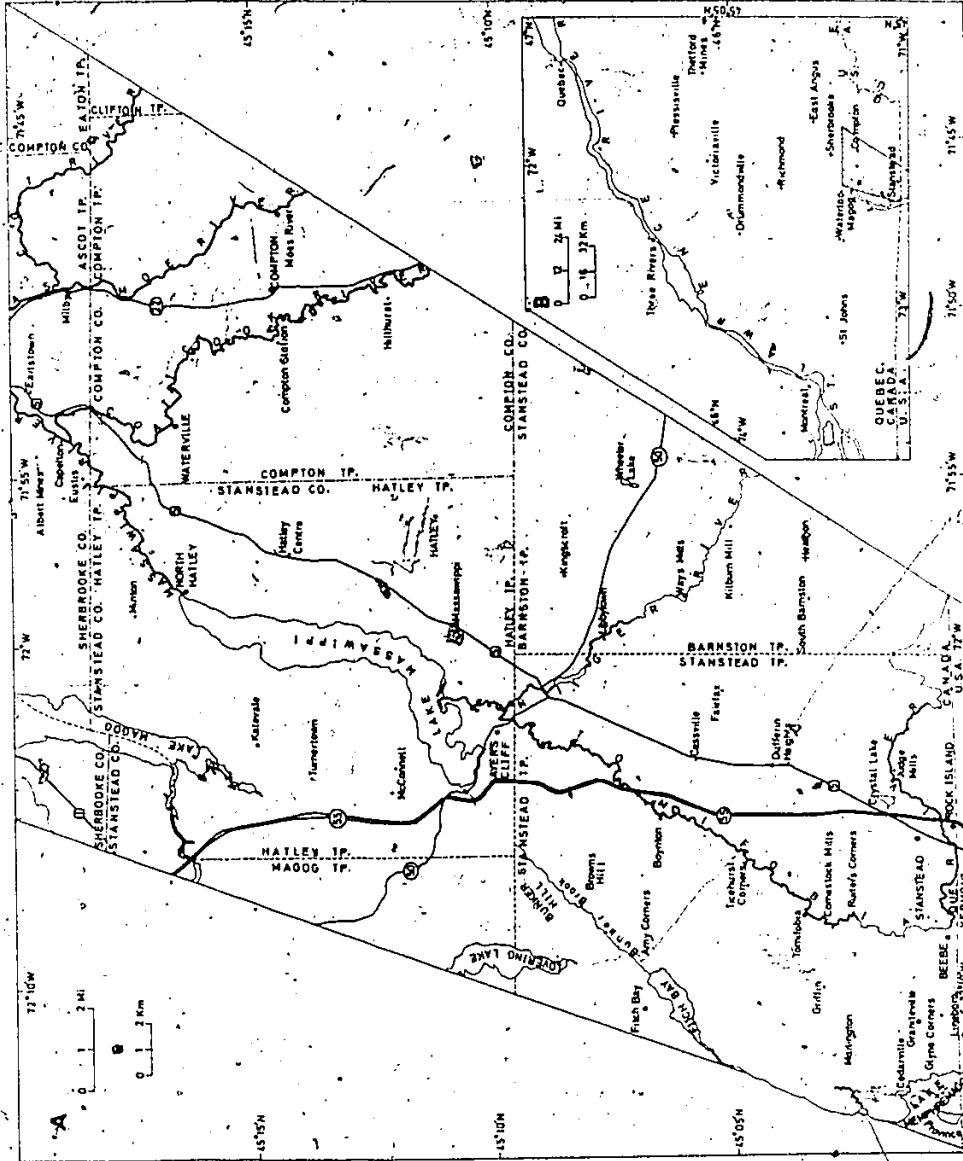


Fig. 1 A) Geographic map, Lake Massawippi area, B) location of study area.

part of Massawippi River to approximately 1,500 feet (400 m) near South Barnston.

About half of the area is farmed; the rest is covered with woods including most of the Stoke Mountains (Fig. 2).

All parts of the study area are easily accessible by a close network of highways and gravel roads. The best exposures of bedrock are along highway 55 which links the Eastern Townships Autoroute (Route 10) with the United States. Elsewhere outcrops are small and far apart, very often having a density of less than one per square mile, the intervening areas being covered by Pleistocene deposits. Most of the outcrops are in small road cuts, however a few are in stream valleys and away from the roads, especially in parts of the Stoke Mountain complex.

#### Geologic Setting

Southeastern Quebec has been divided into several structural domains composed of varying types of rocks. From the Quebec - Maine Border to the west these are the Frontenac syncline, the Connecticut Valley - Gaspé synclinorium, the Stoke Mountain and Weedon Mountain anticlinoria (Cady, 1969), the St. Victor synclinorium (St-Julien, 1967) and the Sutton Mountain anticlinorium (Cady, 1969) (Fig. 2).

Rocks in the Frontenac syncline are predominantly non-calcareous Lower Devonian sediments with a minor amount of volcanics.

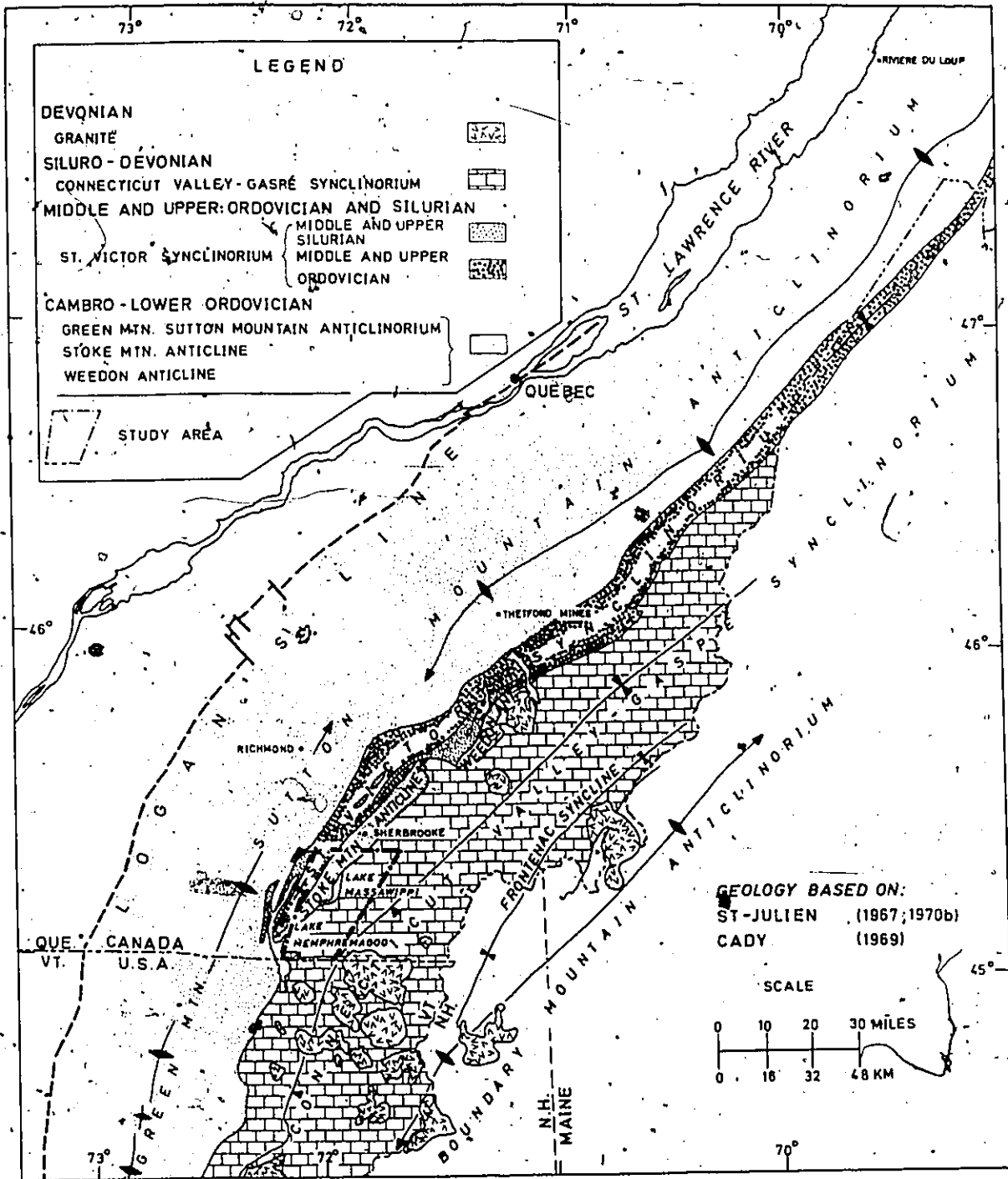


Fig. 2 Geologic map of the Eastern Townships and adjoining areas showing major tectonic units and structures.

The Connecticut Valley - Gaspé synclinorium, which according to some workers includes the Frontenac syncline (Marleau, 1968), extends from Gaspé Peninsula to the southern part of New England. Within it are a series of Siluro-Devonian sedimentary rocks which grade from non-calcareous in the east to calcareous in the west.

Outcropping within the Stoke Mountain and Weedon Mountain anticlinoria are Cambrian or Lower Ordovician metavolcanics and metasedimentary rocks.

Lying within the St. Victor synclinorium are Middle Ordovician non-calcareous sedimentary rocks and Siluro-Devonian limestones.

The Sutton Mountain anticlinorium, which is the northern continuation of the Green Mountain anticlinorium of Vermont, exposes a sequence of Cambrian to Lower Ordovician metavolcanics and metasedimentary rocks which are considered to be equivalent in age to the rocks of the Weedon and Stoke Mountain anticlinoria (St-Julien, 1967).

Rock units in the study area include the Cambrian or Lower Ordovician rocks (Ascot Formation) exposed in the southern tip of the Stoke Mountain anticlinorium, part of the Middle Ordovician rocks (Magog Group) of the St. Victor synclinorium and a portion of the Siluro-Devonian rocks (St. Francis Group) in the Connecticut Valley - Gaspé synclinorium (Fig. 2).

## Previous Work

### Stratigraphic Relations

Following Cady (1960) and others, a summary of previous work defining the stratigraphic relations of the Cambro-Ordovician Quebec Group, and of the Siluro-Devonian "Gaspé Limestones" is given in Tables 1 and 2 respectively. Fig. 3 gives the fossil localities and general stratigraphic relationships for the Eastern Townships and adjoining areas. Table 3 is a correlation by Boucot and Drapeau (in Lamarche, 1962) of the Siluro-Devonian rocks in the Connecticut Valley - Gaspé synclinorium. Fig. 4 indicates the distribution and stratigraphic relations of the main sedimentary, volcanic and intrusive rock units in the vicinity of the study area.

### Structural Relations

Cooke (1957) reported that in the Coaticook - Malvina area (Fig. 3) the major structure is a large homocline formed by overturned sediments at least 14 miles (22.4 km) thick. No explanation, except the possibility of repetition across faults is given for the unusual apparent thickness.

Several detailed structural analyses have been made in Lower Paleozoic rocks to the west and north, and partly within the study area (Fig. 3).

Osberg (1965) studied approximately 300 square miles (768 square km) of Cambrian (?) low-grade metasedimentary and metavolcanic schistose rocks in the Knowlton - Richmond area of the Sutton Mountains about 15 miles (24 km) northeast of

Table 1 Stratigraphic Relations of the Quebec Group: Historical Summary

Rock Unit and Area	Named by, and Date	Worked on by and Date	Age Assigned	Age Based On
QUEBEC GROUP (Megantic hills, Stoke and Sutton mountains and west to Logan's Line)	Logan (1863)		Lower Lower Silurian	
SUTTON MOUNTAIN REGION		Logan (1849)	Middle Lower Silurian	Correlation with Trenton Limestone
		Logan (1863)	Lower Lower Silurian	
Crystalline Schist Group	Selwyn (1879)		Precambrian	Correlation with the Shickshock Mountains, Gaspé
Bennett Schists (Thetford Mines area)	Harvie (1917) and Knox (1917)		Precambrian	
Bennett Schists=Sutton Schists (Sutton area)	Clark (1934)			
Caldwell Series (Beauceville area)	Mackay (1921)		Cambrian	
Bennett Schists = Caldwell Series		Cooke (1932)		
Caldwell Series		Cooke (1937)	Cambrian	
Caldwell Group		Gorman (1954; 1955)	Middle Ordovician	
STOKE MOUNTAIN COMPLEX				
Volcanic Group	Selwyn (1879)		Lower Cambrian	
		Selwyn (1883)	Precambrian	
		Ells (1887)	Precambrian	Correlation of the overlying slates with Cambrian or Lower Cambrian to Silurian rocks in New Brunswick
Stoke Mountains (Eustis area)		Douglas (1941)	Ordovician (sediments) Devonian (volcanics) Cretaceous (dykes)	Cut the sediments Age dating
Sherbrooke Formation	Cooke (1948a)			
		Cooke (1948a; 1950)	Middle Ordovician to Silurian	Fossils in Castle Brook (Fig. 3, fossil locality 5)
Ascot Formation**	St-Julien and Lamarche (1965)		pre-Middle Ordovician	Underly Middle Ordovician rocks

\*equivalent to present Lower Ordovician

\*\*The Ascot Formation replaces the names Caldwell, Sherbrooke and Beauceville Series in the Stoke Mountains, however the terms Sherbrooke and Beauceville are still used for rocks in the St. Victor synclinorium to the west (Fig. 2).

Table 2 Stratigraphic Relations of the "Gaspé Limestones": Historical Summary

Rock Unit and Area	Named by and Date	Worked on by and Date	Age Assigned	Age Based On
Micaceo-calcareous formation	Logan (1849)	Adam (1849) in Logan (1849)	Upper Silurian	Fossils (Fig. 3, fossil localities 1-3)
<b>GASPE LIMESTONES</b>				
	Logan (1863)	Selwyn (1879)	Lower Silurian	
		Selwyn (1883)	Siluro-Devonian	
(North Hatley area)		Ells (1887)	Silurian and Cambro-Silurian	Fossils (Fig. 3, locality 6)
(Famine River and St. Georges, area)		Ells (1869)	Devonian	Fossils
		Ells (1896)	Cambro-Silurian	
(Eaton area)		Weston (1899)	Devonian	Fossils (Fig. 3, locality 7)
<b>ST. VICTOR SYNCLINORIUM</b>				
Magog Formation (Lake Memphremagog area)	Ami (1900)			
Beauceville Series (Beauceville area)	Mackay (1921)		Ordovician	
		Cooke (1933)	Middle to Upper Ordovician	Fossils (Fig. 3, fossil locality 8)
Beauceville Group	Cooke (1948a;b;c)		Middle Ordovician	Fossils (see Cooke, 1933)
Beauceville Group - Magog Formation		Cooke (1950)		
Beauceville Group		Gorman (1954; 1955)	Middle Ordovician	Fossils (Fig. 3, fossil locality 4)
Beauceville Formation - Magog Group		Berry (1962)	Late Middle Ordovician	Fossils (Fig. 3, fossil locality 5)
<b>CONNECTICUT VALLEY - GASPE SYNCLINORIUM</b>				
St. Francis Series	Clark (1937)		Middle Ordovician	Fossils (see Cooke, 1933) (fossil locality presently mapped as Beauceville)
St. Francis Group	Cooke (1948a;b;c)		Ordovician	Based on fossils of Cooke (1933)
Tomifobia Formation	Kerr (1923)			
		Clark (1934)	Ordovician	Fossils (Fig. 3, locality 9)
		Ambrose (1943)	Middle Ordovician	Lithological similarity with the Magog Group (he didn't find the fossils of Ells, 1887)
		Cumming (1953) and McLaren (1953) in Boucet and Drapeau (1968)		Identified the fossils from the locality of Clark (1934) as non-organic
Tomifobia Formation - Ayer's Cliff Formation in Vermont		Doll (1951)	Ordovician	Correlation with the Tomifobia Formation

Table 2 Continued

Rock Unit and Area	Named by and Date	Worked on by and Date	Age Assigned	Age Based On
Compton Formation	McCerrigle (1935)	Kelly (1963)	Ordovician Lower to Middle Devonian	Fossils (Fig. 3, fossil locality 11)
Seeboomook Formation	Perkins (1925)	Pavlidis et al (1964)	Middle-Lower Devonian	
St. Juste Group	Béland (1952)		Siluro - Devonian	Fossils (Fig. 3, fossil locality 10)
Upper and Lower St. Francis Group	Cooke (1950; 1957)		Ordovician	Based on fossils of Cooke (1933)
Upper Upper St. Francis Group = Compton Formation		Marleau (1968)	Lower to Middle Devonian	Based on fossils of Kelly (1963)
Vermont equivalents of St. Francis Group		Doll (1951)	Ordovician to Lower Devonian	Fossils and correlations
Waits River - Gile Mountain sequence		Doll (1961)	Middle Silurian to Lower Devonian	Fossils and correlations
Shaw Mountain Formation	Currie and Jahns (1941)		Ordovician	
		Boucot (1960) see Boucot and Drapeau (1968)	Siluro - Devonian	Fossils (Fig. 3, fossil locality 12)
St. Francis Group		Boucot and Drapeau (1968)	Siluro - Devonian	Fossils (Fig. 3, fossil localities 2 and 13 to 20)
		Lamarche (1965)	Siluro - Devonian	Fossils (Fig. 3, fossil locality 21)
MEGANTIC HILLS		Logan (1863)	Lower-Lower Silurian	
		Ells (1887)	Precambrian	
Frontenac Formation	McCerrigle (1935)		pre-Ordovician	
		Faessler (1939)	Precambrian	
		Marleau (1958; 1968)	Early-Middle Devonian	Correlations

\*The rocks of the St. Victor synclinorium are presently not included with the "Gaspé Limestones" of Logan (1863).

\*\*equivalent to present Lower Ordovician



Table 3 Siluro-Devonian Correlatives in the Connecticut Valley - Gaspé Synclinorium

Standard Sequence	Memphremagog Lake	Lake Aylmer Region to Dudaveil	Lake Etchemin Region	Gaspé	Northern New Hampshire	Eastern Vermont Interpretation "A"	Eastern Vermont Interpretation "B"	Moose River Synclinorium (Maine)	Albany Co. (New York)	New York Column
Late Lower Devonian	Mountain House Wharf Limestone	Upper St. Francis Group	St. Francis Famine Limestone	Grande Grève	Littleton Formation	Gile Mountain Formation	Gile Mountain Formation	Tomhegan Formation	"Schoharie" / grit	Zone "B"
		Lower St. Francis Group (upper part)	St. Luster Group	Cape Bon Ami	Waits River limestone	"Upper" Waits River limestone Frasbury conglomerate	Torrington, Seabrook Formation	Beck Pond limestone	Esopus grit Beecraft ls. Oriskany ss.	Esopus Oriskany Beecraft
Upper Gedinnian									New Scotland Formation	New Scotland
Lower Gedinnian									Manlius Coeymans Formation	Manlius Coeymans
Upper Ludlow										Rondout Cobleskill
Lower Ludlow	Sargent Bay Limestone Glenbrooke Shale	Lake Aylmer Group (lower part)	Cranbourne Series	St. Albans limestone	Fitch Formation	Northfield Slate	"Lower" Waits River limestone (Ayer's Cliff)	Hardwood Mountain Formation		Bertie Salina
		Sherbrooke Group (conglomerate)			Clough Formation	Shaw Mountain Formation				Loc:port Clinton Medina

by Boucot and Drapeau (in Lamarche, 1962)

approximately 60 miles (96 km) southeast of Quebec City



Sherbrooke (Fig. 3). He ascribed first phase isoclinal folds, which trend northwest, to a post-Ordovician and pre-Silurian (Taconic) orogeny. Two subsequent phases of deformation produced isoclinal and open folds respectively, both trending northeast, and these were considered as Upper Devonian (Acadian) structures.

de Römer (1961) mapped a small area (22 square miles; 56 square km) of Cambrian (?) low-grade metasedimentary and metavolcanic schistose rocks in the St. Etienne - de - Bolton area (Fig. 3), which is in the southern part of the area covered by Osberg (1965). He identified two Taconic phases of deformation, that produced isoclinal recumbent folds and open upright folds respectively, that have attitudes similar to the second and third Acadian phases of Osberg (1965). de Römer reported to Béland (1967) that there was evidence of an earlier phase of folding since his  $F_1$  folds folded a previous cleavage; this would be equivalent to the first phase of Osberg (1965).

Rickard (1965) studied an area that extended easterly across the Sutton Mountain metamorphic complex south of that covered by Osberg (1965) and de Römer (1961) (Fig. 3). He also recognized three phases of deformation, which produced nappes, tight upright and recumbent folds, and open folds respectively. He considered that the three phases were Taconic (Middle Ordovician) on the basis that K-Ar age dating of mica in the youngest cleavage plane indicated an age of 440 million years.

The first detailed structural investigation that covered rocks included within the present study area was carried out by Baer (1961) who mapped about 100 square miles (256 square km) west of Lake Massawippi (Fig. 3). He recognized three phases of folding, which produced minor folds and associated cleavages. The first phase also produced macrofolds. The folds and associated cleavages of the second and third phases of deformation were noted to curve in trend and were thought to be due to the diapiric rise of the Acadian granitic bodies to the southeast. He maintained that the Siluro-Devonian rocks of the Connecticut Valley - Gaspé synclinorium contained the same minor structures as the metamorphic rocks in the Stoke Mountain complex and thus considered that all the structures were formed during the Devonian Acadian orogeny.

St-Julien and Lamarche (1965) indicated that early structures, the Sherbrooke and Eustis Anticlines (Fig. 6; in pocket) and minor folds, in the metamorphic rocks in the Stoke Mountains formed during a pre-Normanskill (Lower Ordovician) orogeny. The later structures, a large open fold on the Sherbrooke anticline and minor folds are an expression of the Acadian (Devonian) orogeny.

More recently the outcrop pattern in the Stoke Mountain complex has been reinterpreted from that of St-Julien (1970b), with the identification of major and minor folds of three generations with axial surfaces that strike respectively northward, north to northeastward, and northeastward (Lamarche, 1972a). These are considered to have formed by

the pre-Normanskill (Lower Ordovician), Taconic (Ordovician) and Acadian (Devonian) orogenies (Lamarche, 1973).

The deformation in the Magog Group has been ascribed to the Taconic orogeny (Ordovician) by Lamarche and St-Julien (1969).

Faults: Ambrose (1943) mapped a thrust fault in the Tomifobia River valley (Fig. 1) on the basis of sheared rocks and topographic expression. Doll (1951) considered this fault to be present in Vermont on the basis of stratigraphic and structural relations.

Doll (1951) presented the following arguments for the existence of the Bunker Thrust mapped by Kerr (1923) southwest of Lake Massawippi (Fig. 3). The Ayer's Cliff Formation is much thicker in Canada than it is in the United States, formations pinch out along strike against other formations in Vermont, and there is a displaced marker horizon.

St-Julien and Lamarche (1965) suggested that rocks of the Ascot Formation of the Stoke Mountain complex are bounded and crossed by three southeast dipping thrust faults. On the basis of repetition of strata, a thrust was inferred to lie between the Eustis and Sherbrooke Anticlines within the study area (Fig. 6; in pocket). This was considered by Lamarche (1965) to be the northern continuation of the Bunker Thrust of Kerr (1923).

## Purpose and Scope of the Present Study

From the previous work it is apparent that there is no general agreement as to the age (Taconic or Acadian) of structures within Cambro-Ordovician rocks in the Eastern Townships. The study area was chosen so that it included both Cambro-Ordovician and Siluro-Devonian rocks, the latter obviously not deformed during the pre-Silurian Taconic orogeny. The present work attempts to determine and compare the structural arrangement and history of the two groups of rocks. The following aspects are included:

- 1) The extension of lithological subdivisions of the Siluro-Devonian rocks from the adjacent area in Vermont into the map area.
- 2) The style, mechanical origin, and time order of small scale structures (a) in the Cambro-Ordovician rocks of the southeastern portion of the Stoke Mountain complex (b) in the Siluro-Devonian rocks adjacent to and southeast of the Stoke Mountains.
- 3) Correlation of the polyphase structures described in the Cambro-Ordovician rocks with those in the Siluro-Devonian rocks. This is aided by considering structures previously described within Middle Ordovician to Siluro-Devonian rocks of the St. Victor synclinorium west of the map area.
- 4) The structural phases are related to the Taconic and Acadian orogenies and a tectonic history is outlined and considered in relation to a plate tectonic model.

## Field Procedure

The summers of 1971 and 1972 were spent in the field examining the outcrops along and near the roads. The area was not traversed in detail since the number of outcrops located would be insignificant for the amount of time required. Furthermore, sufficient structural data was obtained from the roadside outcrops to establish various structural events. In addition to lithology, the dip of bedding and other foliation planes, and the trend and plunge of lineations were recorded. For the planar structures the dip direction is referred to throughout the text, rather than the strike; example  $250^{\circ}/60^{\circ}$  indicates a dip of  $60^{\circ}$  towards  $250^{\circ}$ .

The southern part of the Stoke Mountain complex mapped by Lamarche (1965) at 1 inch to 1,000 feet is included in the present area; it was not remapped, although representative outcrops of the various lithologies were visited.

A 1:50,000 map with the numbers of all the outcrop locations is deposited in the Geology Department of the University of Ottawa.

## Acknowledgements

The writer is grateful for the constructive criticism, discussions and suggestions by Dr. W. K. Fyson who supervised the work.

Dr. A. J. Baer, University of Ottawa, is thanked for making available his field data and maps upon which the present study overlaps and for a critical review of the manuscript, and Dr. R. Y. Lamarche, Quebec Department of Natural Resources, for a field trip which included part of the study area. Appreciation is extended to the numerous land owners in the study area who permitted the writer to work on their property, and also to fellow graduates for constructive discussions.

Finally the writer wishes to acknowledge financial support by the National Research Council of Canada via grants to Dr. W. K. Fyson, as well as support by the University of Ottawa. E. W. Hearn took the photomicrographs and made constructive suggestions in relation to the drafting.

II

STRATIGRAPHY

Introduction

The rock units relevant to the study are summarized in Table 4 and the distribution and stratigraphic relations of those mapped in the study area are shown in Fig. 5.

Most of the rocks of the Stoke Mountain complex are unfossiliferous metasediments and metavolcanics of the Cambrian or Lower Ordovician Ascot Formation.

The Magog Group outcrops to the northeast of the Stoke Mountains in the St. Victor synclinorium (Fig. 2). The Group includes the Middle Ordovician Beauceville Formation composed of fossiliferous slate and siltstone, and the Upper Ordovician fossiliferous Sherbrooke and equivalent (?) East Branch Pond Formations consisting of sandstone and slaty members. Disconformably overlying the Magog Group are the Middle Silurian to Devonian fossiliferous slates and calcareous rocks of the Glenbrooke Group. The Lake Aylmer Formation unconformably overlies the Magog Group.

On the southeastern side of the Stoke Mountains, in the Connecticut Valley - Gaspé synclinorium, a sequence of limestones, limy slates, calcareous sandstones and non-calcareous slates and sandstones forms the St. Francis Group (part of the "Gaspé Limestones" of Logan, Table 2). To the northeast it is correlated with Middle and Upper Silurian to

Table 4 Table of Formations

Age	Group	Formation, Member and Intrusive Rocks	Map Unit**	Description
Cretaceous (?)		Dykes		lanaprophyre dykes
Upper Devonian (?)		Diorite	I4	carbonatized
Middle or Upper Devonian		Granite	I3	massive Na-rich fresh granite
Middle Silurian to Devonian	Glenbrooke Group and Lake Aylmer Formation*		**	limestone, slate and sandstone
	Upper St. Francis Group	Gile Mountain Formation (Vermont) Westmoir Member	F4	quartzose slate, phyllite and sandstone (locally calcareous)
Lower Devonian		Waits River Formation (Vermont) Barton River Member	F3	calcareous slate, sandstone and limestone
	Lower St. Francis Group	Ayer's Cliff Member	F2	siliceous limestone, graphitic limy slates, minor dolomite
Middle and Upper Silurian		Northfield Formation	F1	black siliceous slate
UNCONFORMITY				
Upper Ordovician	Magog Group	Sherbrooke and East Branch Pond Formation	**	conglomerate sandstone and slate
Middle Ordovician		Beauceville Formation	M1	slate and siltstone
UNCONFORMITY				
		Granite	I2	altered, chlorite rich rock with quartz and albite
		Ultramafic Rocks	I1	altered ultramafic (ankerite rich) rocks containing altered serpentine veins
			A4	sericite (chlorite) schist
			A3	graphitic phyllite
			A2	siltstone, sandstone, thin bedded tuffaceous (?) rocks and chert
Lower Ordovician to Cambrian		Ascot Formation	A1	massive greenstone, chlorite schist, meta-rhyolite, rhyolite porphyry, feldspar-quartz-sericite schist

\*The St. Francis and Glenbrooke Groups, and the Lake Aylmer Formation are considered to be stratigraphically equivalent.

\*\*Double asterisks in the map unit column indicate that the unit was not mapped (the units do not appear on the stratigraphic map, Fig. 5) although brief surveys were made.

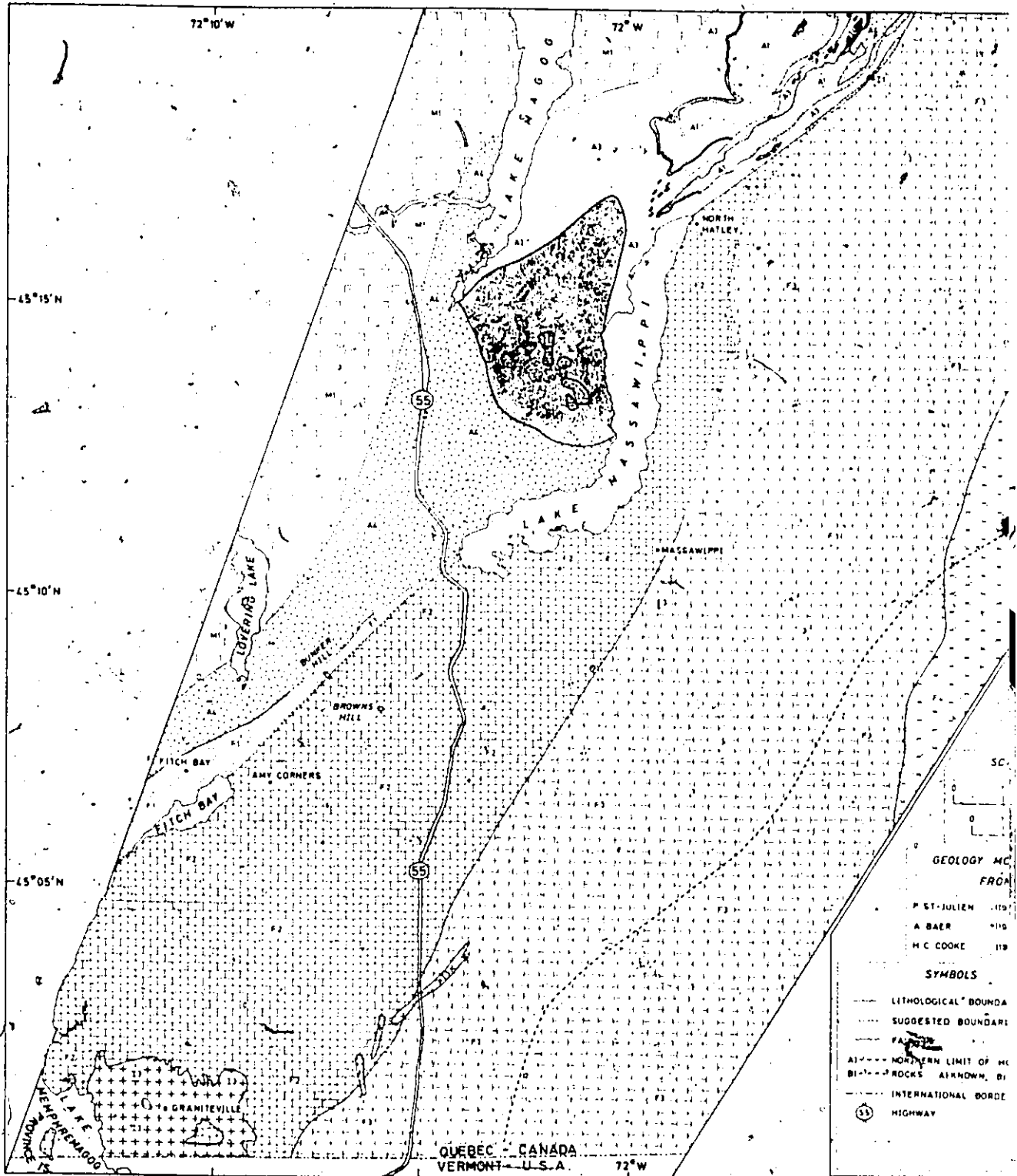
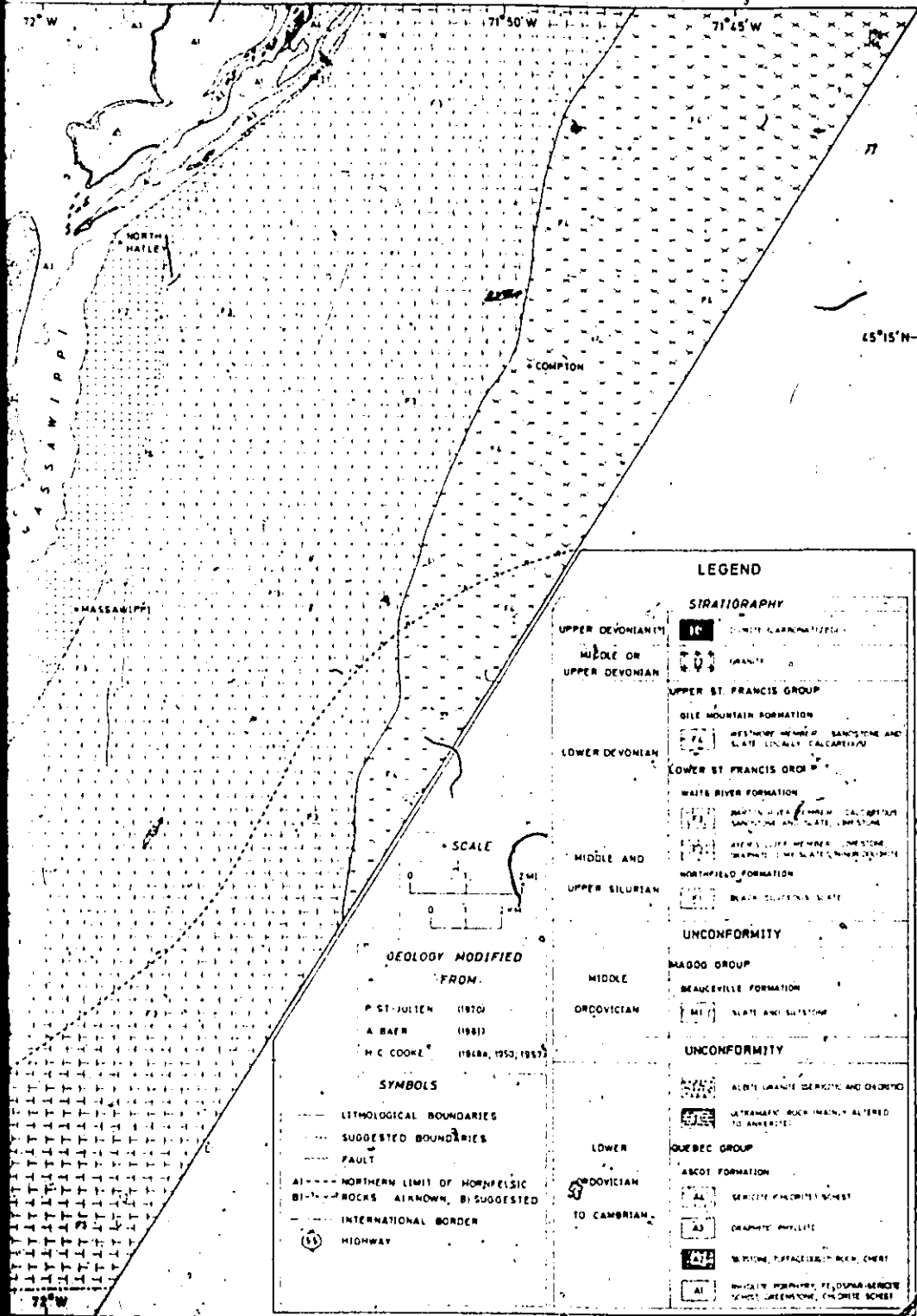


Fig. 5 Stratigraphic map of the Lake Massawippi

11 of



Geological map of the Lake Massawippi area.

2 of 2

Devonian rocks (Table 3).

The present study involved the mapping of the southern part of the Ascot Formation using rock units defined by St-Julien and Lamarche (1965) to the north. Within the St. Francis Group units that Doll (1951) established for the adjacent area in northern Vermont were extended northward.

### Cambrian to Lower Ordovician Rocks

#### Ascot Formation

Only a brief description of the major lithological subdivisions of the Ascot Formation is presented here. For a more detailed account see Lamarche (1965; 1967) and St-Julien and Lamarche (1965). The various map units, A1 to A4, (Table 4 and Fig. 5) are not necessarily in stratigraphic order. Moreover some are, in part, stratigraphic equivalents and the outcrop distribution shown (Fig. 5) is open to reinterpretation. For example the pattern north of Lake Massawippi which follows that compiled by St-Julien (1970b) has recently been extensively modified in a sketch map by Lamarche (1972a).

Acid Volcanics (map unit A1): Rocks of this unit outcrop in a northeasterly trending belt in the Stoke Mountains in the northern part of the study area (Fig. 5). The rocks include rhyolite porphyry, metarhyolite and feldspar-sericite schist, greenstone and chlorite schist. A small amount of intrusive rhyolitic porphyry containing albite and quartz phenocrysts.

has been included in this unit. The rock types were mapped separately by St-Julien and Lamarche (1965); but they appear to intergrade along strike.

Common minerals include albite, quartz, chlorite, ankerite, epidote, actinolite and sericite. Pyrite is locally common.

St-Julien and Lamarche (1965) are of the opinion that the chlorite schists originated from metamorphosed intermediate basic tuffs as well as from a mixture of pyroclastic and detrital material.

Siltstone, Sandstone, Tuffaceous (?) Rocks and Chert (map

unit A2): Rocks of this unit outcrop in narrow zones adjacent to unit A1. As mapped by St-Julien and Lamarche (1965) the rocks appear to occupy several stratigraphic horizons and possibly they should not be grouped into a single stratigraphic unit.

A large outcrop area of siltstone and tuffaceous (?) rocks is also present between the western side of the central part of Lake Massawippi and the southern tip of Lake Magog (Fig. 5).

The siltstones and thinly bedded (from several mm to about 3 cm) tuffaceous (?) rocks are generally weathered to a dull, grayish brown pitted surface. The composition is predominantly quartz with varying minor amounts of plagioclase, ankerite, sericite, chlorite, epidote and pyrite in a very fine matrix of phyllosilicates. The tuffaceous (?) rocks contain more sericite which, most probably, resulted from alteration of feldspars. Nearly pure, gray, quartz sandstone is present in several outcrops.

Chert forms a very minor part of the unit within the study area. It usually occurs in thin discontinuous reddish bands.

West of Lake Massawippi the contact of unit A2 with unit A3, to the northwest, and with unit A4 to the southeast (Fig. 5) was not directly observed; however the distribution of small outcrops appears to indicate a gradational contact with unit A4, and a sharper contact with unit A3. To the northeast, the contact between units A2 and A1 (Fig. 5), where-ever observed is sharp.

Graphitic Phyllites (map unit A3): Dark graphitic phyllites, probably originally carbonaceous mudstones, are widespread in the northern part of the outcrop belt of the Ascot Formation. They extend from the outcrop area of unit A2 west of Lake Massawippi to the northeast where they surround map units A1 and A2 (Fig. 5). The phyllites disintegrate rapidly when exposed to air so that natural outcrops tend to be restricted.

The dominant minerals, in order of abundance, are quartz, sericite, graphite and a minor amount of chlorite. Pyrite cubes are abundant throughout the unit.

Sericite (Chlorite) Schist (map unit A4): Rocks of this unit outcrop to the west and south of Lake Massawippi in a belt one to five miles (1.6 to 8 km) wide between the Magog and the St. Francis Groups (Fig. 5). Chlorite-sericite schists are also present to and beyond the northern border of the map area. In places the schists pass along strike into feldspar-sericite schists or metarhyolite of unit A1 (St-Julien, 1970b)

hence a partial stratigraphic equivalence is suggested.

The position of small outcrops of unit A2 and A4 indicates that their contact is gradational. The map pattern (Fig. 5) suggests that unit A4 is stratigraphically equivalent to the graphitic phyllites of unit A3.

The chlorite-sericite schists are composed predominantly of quartz, sericite, plagioclase, ankerite and chlorite. The quartz grain size ranges from that of a micro-conglomerate to that of a slate. The composition and grain size variations suggest that the rocks are the product of the alteration of graywacke and mudstone.

Rocks of unit A4 are slaty westward near the contact with the Beauceville Formation (Magog Group). Here outcrops are scarce so that the contact could only be located approximately. Towards the southwest chlorite becomes a negligible component and the rock grades into a quartz-sericite schist.

#### Stratigraphic Relations of the Ascot Formation with the Magog and St. Francis Groups

The contacts between rocks of the Ascot Formation and adjacent rocks of the Magog Group (Middle Ordovician Beauceville Formation and Upper Ordovician Sherbrooke and East Branch Pond Formations) to the northwest, and the Middle Silurian to Lower Devonian St. Francis Group to the southeast are obscure, both within and outside the study area.

A white arkosic graywacke consisting of well rounded to sub-angular rhyolitic fragments and albite and quartz grains forms the base of the Beauceville Formation (Lamarche, 1967).

Following Lamarche (1967) the clasts are considered to be derived from the Ascot Formation or associated intrusive rocks of the Stoke Mountain complex. Thus the Beauceville Formation is interpreted as lying unconformably on the complex. The fossil bearing Beauceville Formation is Middle Ordovician (Berry, 1962), and hence the Ascot Formation is considered (Lamarche, 1965; 1967; 1972a; St-Julien, 1970b) to be Cambrian or Lower Ordovician.

It follows that rocks of the Siluro-Devonian St. Francis Group on the east side of the Stoke Mountain complex also lie unconformably above the Ascot Formation. The relationship is also supported by the presence of fragments of siltstone, slate, felsic volcanic rocks and albite in a conglomerate of the St. Francis Group that appears to be derived from the adjacent Ascot Formation (Lamarche, 1967).

#### Ultramafic Rocks (map unit Il)

Ultramafic rocks are present in two small outcrop areas northwest of Lake Massawippi and in other outcrop areas northeast of North Hatley (Fig. 5). The rocks are dark green and massive, retrogressively metamorphosed peridotite, predominantly composed of (in order of abundance) ankerite, chlorite, talc and minor quartz (possibly secondary). Veins, up to 2 cm in width, of fibrous serpentine, partially altered to talc, are present throughout the rock. The contact relations of the ultramafic rocks and the possible age of emplacement are not clear. For a more detailed account see Lamarche (1965).

Albite Granite (map unit I2)

Near the ultramafic rocks northwest of Lake Massawippi are two small outcrop areas of altered granitic rock (Fig. 5). A large outcrop of similar granitic rock is present northeast of Sherbrooke beyond the limits of the map area (Fig. 3). The granite is foliated and composed predominantly of quartz and plagioclase (mainly albite) with minor sericite and chlorite (Plate Ib).

North of the map area the granite crosses structures in the Ascot Formation. Fragments of similar albite granite are present at the base of the Middle Ordovician Beauceville Formation and the Upper Ordovician Sherbrooke Formation (Lamarche, 1965), hence it appears to be pre-Middle Ordovician, but younger than the Ascot Formation.

Radiometric data from lithologically similar albite granite northwest of Sherbrooke (Fig. 3,  $45^{\circ} 26' 00''$  N and  $71^{\circ} 48' 44''$  W) indicate a K-Ar age of  $322 \pm 14$  million years for muscovite (Wanless, Stevens, Lachance and Edmonds, 1968) and a Rb-Sr whole rock isochron age of 384 million years (Wanless, 1969; compiled from unpublished data). On the geological time scale these are Devonian or Carboniferous ages. However the K-Ar age most probably reflects Devonian (Acadian) or younger deformation and low grade metamorphism rather than the age of the initial cooling of the granitic material. Why the Rb-Sr whole rock isochron age, believed to be a more reliable indicator, is considerably younger than Ordovician is not fully understood, however the  $Sr_{87}/Sr_{86}$  ratio is high (numerical values unpublished) thus possibly indicating that

the date has most likely been updated (W. H. Poole, 1973 written communication).

## Middle and Upper Ordovician Rocks

### Magog Group

Beauceville Formation (map unit M1): The few exposures of slate and siltstone of the Beauceville Formation that occur within the study area are on the northwestern side of the Assot Formation (Fig. 5). The dominant mineral, quartz, occurs in a fine grained matrix and minor feldspar and muscovite (sericite) is also present. Rocks in the formation are considered to be Middle Ordovician because of Middle Ordovician fossils at Castle Brook (Fig. 3, fossil locality 5). (Berry, 1962).

Sherbrooke and East Branch Pond Formations: The fossiliferous Upper Ordovician Sherbrooke Formation, which outcrops north of the study area, (Fig. 4) is considered by St-Julien (1970b) on the basis of lithology (conglomerate, sandstone and slate) to be equivalent to the East Branch Pond Formation, which lies further west (Fig. 4). On indirect evidence Lamarche (1962) suggested that an angular unconformity exists between the East Branch Pond and the Beauceville Formations but, as indicated by St-Julien (1963a), there is probably a disconformity.

Lamarche (1967) indicated that the Sherbrooke Group

unconformably overlies the Beauceville Formation about 5 miles (8 km) north of Sherbrooke (Fig. 3). On the other hand, the formations appear to be disconformable (St-Julien, 1963a, p. 9) about 4 miles (6.4 km) west of Sherbrooke. Moreover, in the Disraeli area about 45 miles (72 km) northeast of Sherbrooke (Fig. 4) the Sherbrooke and Beauceville Formations are apparently conformable (St-Julien, 1970a). Hence it seems that if there is an angular unconformity between the formations it is local and not indicative of widespread tectonic deformation. This conclusion is of importance for the correlation of structures in the study region and the tectonic synthesis (Chapter IV).

#### Middle Silurian to Devonian Rocks: St. Francis Group

For fossil localities, a discussion of the ages assigned to the St. Francis Group, and stratigraphic equivalents see Fig. 3 and Tables 2 and 3.

#### Northfield Formation (Lower St. Francis Group) (map unit F1)

Rocks of this unit are of similar aspect and structural position to the Northfield Slates (Doll, 1951) of Vermont. The rocks are present to the southeast of the Ascot Formation in a few outcrops west of Fitch Bay and in a northeasterly extension in a narrow outcrop zone at the base of Bunker Hill (Fig. 5). Further northeast there is little or no exposure. Similar rocks were reported (Doll, 1951) to be present 1.5 miles (2.4 km) southwest of Lake Massawippi, but this locality

was not found during the present study.

The rock is a very fissile lustrous black slate. The fine quartz phyllosilicate matrix is locally slightly calcareous, and there is a minor amount of pyrite and aligned sericite. A few coarser grained thin silty quartz-rich layers are present.

Due to its silvery black lustre, uniformly fine grain size and locally slightly calcareous nature it is readily distinguished from slates of the Beauceville Formation (map unit M1), Magog Group, which tend to be non-calcareous dull brown to dull gray and with more prominent coarser grained silty layers.

Doll (1951) considered the slates in Vermont to be in thrust fault contact with the Ayer's Cliff Formation (map unit F2) to the southeast, but no direct contact between the two units was observed in the study area.

#### Waits River Formation (Lower St. Francis Group)

Ayer's Cliff Member (map unit F2): The term Ayer's Cliff Formation was used in northern Vermont (Doll, 1951), but with the type section near Ayer's Cliff in the present study area (Fig. 1). The rock unit was later relegated to a member of the Waits River Formation (Doll, 1961). This member occurs southeast of map units F1 and A4 (Table 4) in a northeast trending belt that is about 6 miles (9.6 km) wide at the southern limit of the map area decreasing to about 2 miles (3.2 km) wide at Lake Massawippi. Due to the lack of

exposures the unit could not be traced with certainty further northwest than Massawippi (Fig. 5)

The rocks are a monotonously uniform sequence of dominantly dark gray, and locally light gray, massive to laminated siliceous limestones with occasional silty quartzose beds. They are well exposed along highway 55 from about 1 mile (1.6 km) south of the junction of highway 55 and highway 50 to about 2.5 miles (4 km) north of the International Border (Figs. 1 and 5). Interbedded with the limestones are occasional light reddish dolomitic beds (weathered surface) ranging in thickness from several centimetres to 1 or 2 metres (Plate IIa) composed mainly of dolomite, some quartz and minor calcite.

In the vicinity of Browns Hill and Amy Corners (Figs. 1 and 5) near the contact with unit F1 some fissile dull gray graphitic calcareous slates and slightly more siliceous rocks are present, which suggest a lithological gradation between the units.

Throughout unit F2, in addition to calcite and quartz, minor biotite, muscovite (sericite) and altered plagioclase feldspars are present.

Doll (1951) estimated the unit to be 4,500 feet (1,363 m) thick in Vermont, however the presence of tight folds of several generations and possibly many faults make any estimate doubtful.

Barton River Member (map unit F3): The term Barton River Formation was used by Doll (1951) for rocks in Vermont (Barton

River Member, Doll, 1961) and it has been retained for adjacent rocks in the present study area. Rocks of this unit are present to the east and north of the Ayer's Cliff Member in a northeast trending belt about 7 miles (11.2 km) wide that extend north and south beyond the map area (Fig. 5).

The western and apparently basal part of the sequence is made up of interbedded slates, limy slates, phyllites, and minor amounts of calcareous sandstones and limestones. This grades eastwards into a dark coloured laminated limestone, the dominant rock type in the unit, with a few thin sandstone or slate beds. These rocks grade further eastward to calcareous slate and phyllite which are predominantly more siliceous.

The limestones are a duller gray and generally lack the thin siliceous laminae that are present in the Ayer's Cliff Member. The association with sandstone and slate is distinctive of the Barton River Member.

The contact of unit F3 with the Ayer's Cliff Member was not seen in any one outcrop. It is placed where the dark gray siliceous limestones of the Ayer's Cliff Member give way to interbedded slates and limy slates. The contact crosses highway 55 about 3 miles (4.8 km) north of the International Border (Fig. 5).

At a few localities the basal western part of the unit has large elongated calcareous quartz siltstone "boulders" approximately 1 foot (30 cm) across, in a weathered out calcareous slate. The "boulders" may originally have been part of a continuous bed that during deformation was extended

within a more ductile calcareous slate matrix to form separated boudins (also see p. 58).

In Vermont the basal (Irasburg) conglomerate is composed of a matrix similar to the limestone of the Ayer's Cliff Member (Doll, 1951). Included are rounded to sub-angular clasts of granite, andesite, diorite, diabase, serpentine, chlorite and sericite schist, marble, quartzite and phyllite. In contrast to the Ayer's Cliff limestone the conglomerate indicates a high energy environment of deposition, and the clasts appear to be partly derived from the Stoke Mountain complex thus suggesting uplift (faulting?).

Slump structures are very common in the Barton River Member (Plate IIb) especially in the more calcareous rocks. Flame structures (Plate IIIa) and cross-bedding (Plate IIIb) in calcareous sandstones are occasionally present. Although an insufficient number of top directions were observed to generalize about the directions the beds face the primary structures identified indicate that the beds are overturned to the southeast.

In addition to calcite and quartz the Barton River Member is composed of altered plagioclase, minor sericite and biotite and a trace of chlorite and tourmaline. The biotite is detrital (crystals are oriented at random) as well as post-tectonic (crystals cross-cut the foliation planes) (also see p. 66-67). The amount of quartz increases in the siliceous rocks to the southeast (Fig. 5, towards unit F4).

Doll (1951) reported finding garnet, staurolite, andalusite, tourmaline, calc-silicates, and chlorite as well as other

metamorphic minerals in the adjacent area in northern Vermont, however, apart from minor chlorite and tourmaline these minerals are not present within the study area.

In the south of the area near a large Devonian granitic pluton (Fig. 5, map unit I4) the rocks in unit F3 are hornfelsic. There is little obvious mineralogical change, with the exception of the minor addition of biotite.

Doll (1951) estimated the thickness of unit F3 to be 8,800 feet (2,672 m), but this estimate is suspect due to the scarcity of outcrops, the presence of folds and faults, the lack of stratigraphic tops and the monotony of rock type without mappable marker horizons.

#### Gile Mountain Formation (Upper St. Francis Group)

Westmore Member (map unit F4): This term was used by Doll (1951) in Vermont but later replaced by the Gile Mountain Formation (Doll, 1961). It has been retained as a member for rocks in the present study area since the Upper St. Francis Group (in Quebec) has been further subdivided into units that have not been separated in the Gile Mountain Formation (in Vermont). Rocks of the unit extend along the margin of the map area east of the Barton River Member (map unit F3) (Fig. 5). The exposures are very limited because most of the bedrock in this area is covered by Pleistocene deposits.

The principal rock types are interbedded light to darker coloured quartzose slates with some phyllites and gray sandstones and limestones. The calcareous rocks are mainly near the contact with the Barton River Member. In contrast

to the dark calcareous rocks characteristic of the Barton River Member these rocks are not nearly as uniform in grain size, and the beds in the slates and sandstones are generally lighter coloured and individually more prominent.

The rocks are predominantly quartz rich, and, as in the Barton River Member, there are minor amounts of biotite, sericite and altered plagioclase feldspar. Pyrite is common throughout the unit. The metamorphic minerals, tourmaline, zircon, garnet, epidote and staurolite that Doll (1951) reported to be in rocks of this formation in northern Vermont have not been observed, with the exception of tourmaline, within the study area.

Doll (1951) suggested 4,300 feet (1,300 m) as the thickness of the unit, however, as indicated for the other units the estimate is questionable.

The change in lithology from the Barton River Member to the Westmore Formation is gradational. For example, in the slaty rocks the gradational colour change from dark calcareous to lighter quartzose-rich rocks plays an important part in the field separation. The rocks characteristic of each unit are interbedded over a zone up to about 2 miles (3.2 km) wide. Thus it is impossible to exactly locate the contact. As drawn on the map (Fig. 5) it closely follows the boundary between the Upper and Lower St. Francis Group of Cooke (1948a, b, c; 1950; 1957).

Doll (1951) placed the eastern boundary of the Barton River Member in the adjacent area in Vermont considerably further to the west than it is shown within the map area.

However his boundary appears to be controlled by the degree of metamorphism as it closely corresponds to the western limit of the hornfelsic rocks (Fig. 5).

Although stratigraphic tops are not common, those that were observed indicate that the beds are overturned and face southeast so that the rocks of unit F4 appear to be younger than those of F3. It is possible that there is also a lateral facies change, as suggested by Doll (1961) and Boucot and Drapeau (1968). Unlike Doll (1961), who indicates that the Waits River Formation (Lower St. Francis Group) and the Gile Mountain Formation (Upper St. Francis Group) are complete stratigraphic equivalents, in the present interpretation following Boucot and Drapeau (1968), see also Table 3, only the top of one unit and the basal part of the other are considered as possible time equivalents.

#### Middle Silurian to Devonian Rocks: Glenbrooke Group and Lake Aylmer Formation

---

The Glenbrooke Group and Lake Aylmer Formation, which lie to the west and north of the study area (Fig. 4) are correlated with the St. Francis Group on the basis of fossils (Boucot and Drapeau, 1968). They all have similar lithologies (limestone, slate and sandstone). Drapeau (1961) indicated that an unconformity exists between the Glenbrooke Group and the underlying Beauceville Formation. However, the contact was not observed and there are no obvious differences in the structures of the two units. Lamarche (1962) placed the

Glenbrooke Group and the Upper Ordovician (?) East Branch Pond Formation as conformable, but since Lower Silurian rocks are missing they must be separated by a disconformity.

Limestones of the Lake Aylmer Formation directly overlie the Middle Ordovician Beauceville Formation 0.5 mile (0.8 km) west of the Stoke Mountain complex north of Sherbrooke (Fig. 4). Further west conglomerates in a small outcrop area considered to be a remnant of the Lake Aylmer Formation appear to rest on the Upper Ordovician Sherbrooke Formation and an unconformity is indicated (Lamarche, 1967). However the outcrop pattern for the Lake Aylmer Formation indicates that it is preserved in synclinal structures that extend into the Sherbrooke and Beauceville Formations (Fig. 4) and there is no obvious local structural discordance. The arrangement suggests that the unconformity is the result of uplift and erosion of the underlying rocks with little local deformation. It is significant that the Sherbrooke Formation is absent from below the Lake Aylmer Formation in the area close to the Stoke Mountain complex, as to be expected if the complex was a positive block.

#### Middle or Upper Devonian Rocks

##### Granite (map unit I3)

Several granitic plutons outcrop near and across the International Border (Figs. 3, 4 and 5) the largest occurring 33 miles (52.8 km) east of Lake Memphremagog. The rock is unfoliated and fresh (Plate Ia) and the dominant minerals,

with approximate percentages, are quartz 25%, plagioclase (oligoclase-andesine) 60% with lesser amounts of potassium feldspar (microcline and microperthite) 5-10%, biotite 4%, muscovite 1%, and traces of hornblende, sphene, epidote and apatite; percentages are based on two samples.

Doll (1951) recorded in Vermont a folded granitic sill in the Barton River Member as well as boudins in granitic veins. Both the sills and the veins appear to be comagmatic with the granitic plutons which elsewhere are undeformed and cross-cut the folded Siluro-Devonian country rock. Evidently granitic material was emplaced in part before and in part after the regional deformation. The granites are thus, in the general sense, partly syntectonic.

The granites and pegmatites of New England are dated as 290-340 million years (Faul et al, 1963; Fairhairn et al, 1960 and Damon and Kulp, 1957, in Lyons and Faul, 1968) and more recently as 310-450 million years (Green, 1964; Faul et al, 1963, in Lyons and Faul; 1968). These are predominantly Devonian dates; the older dates being in New Hampshire and Massachusetts. Page (1968) considers all these granites to be post Lower Devonian regardless of their radiometric ages. He also considers that the granites of northern Vermont and southern Quebec belong to a late Devonian plutonic series. As the granites cross-cut folds in Siluro-Devonian rocks the folding must be of Devonian age.

## Upper Devonian (?) Rocks

### Diorite (map unit I4)

Undeformed, but partly carbonatized diorite is present in narrow dykes and sills along the foliation planes in a band that extends from Lake Massawippi northeast beyond the map area (Fig. 5). The outcrops tend to follow the fault mapped by St-Julien and Lamarche (1965) between the Eustis and Sherbrooke Anticlines (Fig. 6; in pocket). The undeformed diorite intrusions appear to be late or post Devonian features.

## Cretaceous (?) Rocks

### Dykes

Fine grained lamprophyre dykes from several centimetres to a metre or two in thickness are common in all lithologic units throughout the study area.

Doll (1951) considered the dykes to be Devonian in age, but Lamarche (1967; 1972a) has related them to the Mesozoic Monteregian Plutons.

III

STRUCTURES

Introduction

Three individual phases of widespread deformation (Tectonic I-III) are recognized as having produced small scale structures within rocks of the study region. However, because the correlation between groups is not unequivocal, the succession of small scale structures is mapped separately for each group (Fig. 6; in pocket) and the characteristics are separately tabulated (Tables 5 to 8) and discussed. The major structures inferred from the minor structures and the outcrop patterns are then considered and finally, taking into account the average orientations (Figs. 7; in pocket, and 8) and the form, the structures are correlated and assigned ages (Table 9).

Ascot Formation

The main characteristics of the structures in the Ascot Formation are summarized in Table 5.

D<sub>1</sub> Deformation

F<sub>1</sub> Folds: Micro and mesoscopic F<sub>1</sub> intrafolial folds are present in phyllites and schists (Fig. 10 and Plate IV). However the closures are rarely exposed. A foliation, S<sub>1</sub>,

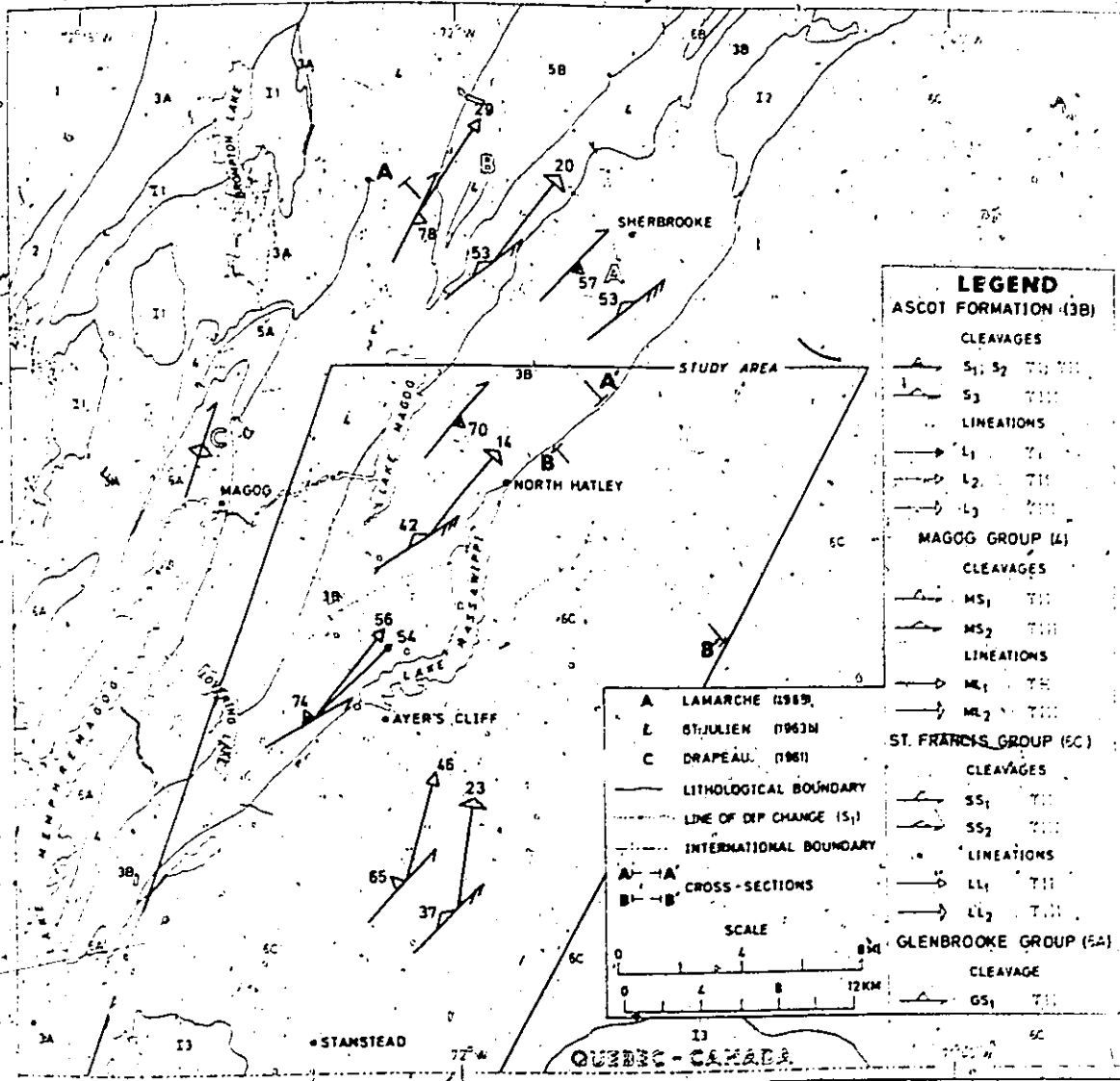


Fig. 8 Map of modal average orientations of structures, Lake Massawippi area, Magog area (from Drapeau, 1961), and Sherbrooke area (from St-Julien, 1963b, and Lamarche, 1965). Numbering of the lithological units corresponds to Fig. 4. I1 is Lower Ordovician gabbro, minor biotite granite and ultramafics, I2 is Lower Ordovician granite, I3 is Middle or Upper Devonian granites. 5B is the Upper Ordovician Sherbrooke Formation. The symbols T1 to TIII correspond to the Tectonic deformational phases as correlated in Table 9.

A modal value of  $056^{\circ}/18^{\circ}$  given by Lamarche (1965, Fig. 10, p. 198) for an L<sub>2</sub> lineation, equivalent to L<sub>3</sub> in the present study, has been omitted from the Ascot Formation because it does not lie on his modal S<sub>2</sub> (equivalent to S<sub>3</sub>) (1965, Fig. 7, p. 190) plane.

See Fig. 9 for cross sections.

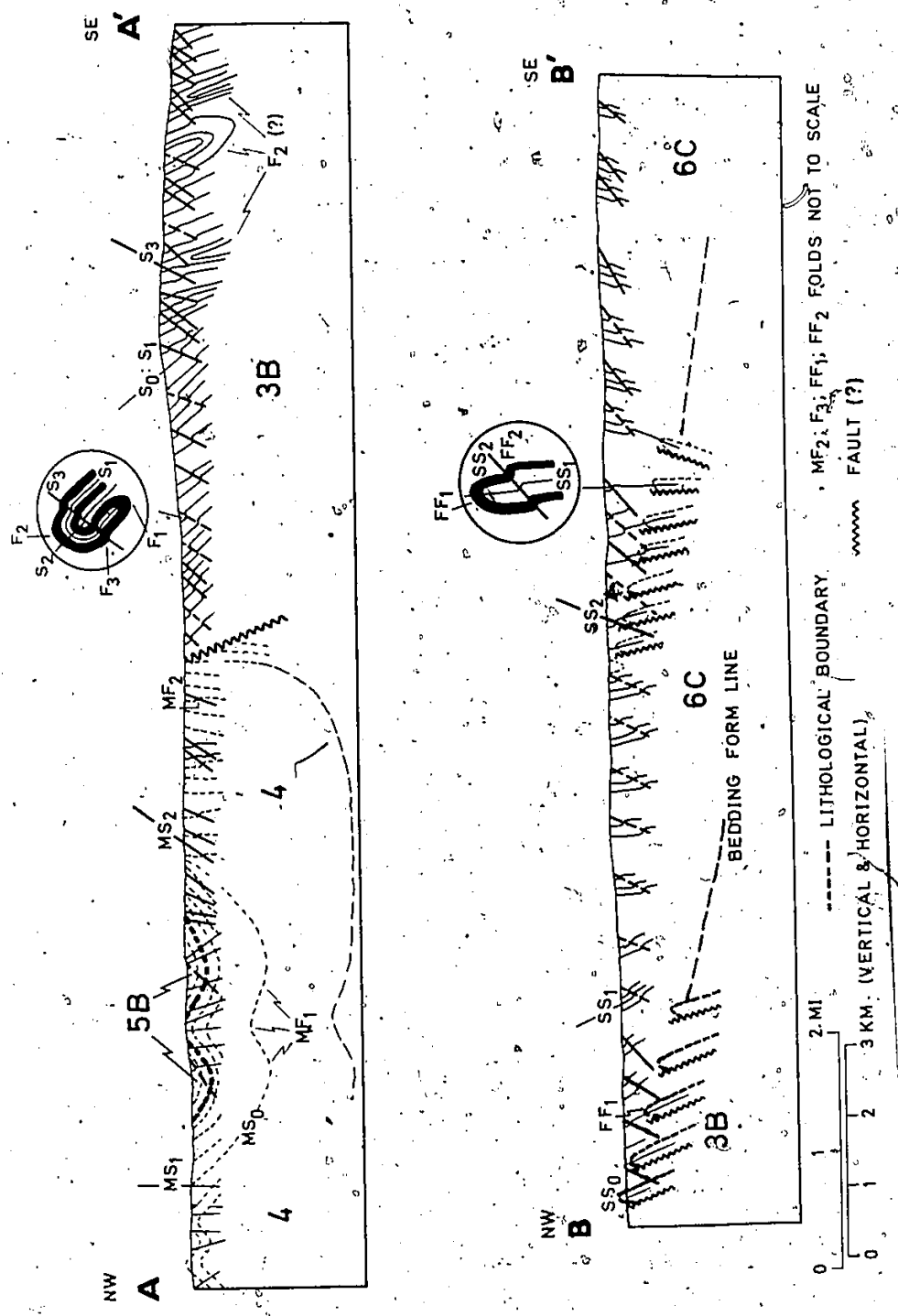


Fig. 9 Cross sections of the study area and surrounding district. Rock units are labelled as in Fig. 8.

Table 5 Characteristics of Structures: Ascot Formation (Cambrian or Lower Ordovician)

Phases of Deformation	D <sub>1</sub>	D <sub>2</sub>	D <sub>3</sub>
Folds	F <sub>1</sub>	F <sub>2</sub>	F <sub>3</sub>
Folded Surface	S <sub>0</sub> (bedding)	S <sub>0</sub> ; S <sub>1</sub>	S <sub>0</sub> ; S <sub>1</sub> ; S <sub>2</sub> (if present)
Shape and Approximate Interlimb Angles	near isoclinal 10°-25°	close - tight 20°-50°	open - close 40°-120°
Ramsay's (1967) Class	1C	1B; 1C; 2 (few)	1C, 3 (few)
Observed Scale	micro - meso - macro (?)	meso	few micro - meso - macro
Axial Plane Cleavage	S <sub>1</sub> : penetrative schistosity, slaty and fracture cleavage	S <sub>2</sub> : local crenulation and fracture cleavage in axial areas only	S <sub>3</sub> : penetrative crenulation and fracture cleavage
Axial Lineation	L <sub>1</sub> : colour banding due to S <sub>1</sub> /S <sub>0</sub> intersection	L <sub>2</sub> : fine striations due to S <sub>1</sub> /S <sub>2</sub> intersection	L <sub>3</sub> : crenulations and colour banding due to intersections of S <sub>0</sub> /S <sub>3</sub> and S <sub>1</sub> /S <sub>3</sub>
Orientation (modal values)	S <sub>1</sub> : 330°/74° in southwest n <sup>*</sup> =45 131°/70° in northwest n=29  L <sub>1</sub> : (K <sup>**</sup> ) 041°/54° n=30 L <sub>1</sub> : 056°/47° n=30	S <sub>2</sub> : parallel to S <sub>1</sub>  L <sub>2</sub> : (K) 030°/78° n=42 L <sub>2</sub> : 044°/56° n=42	S <sub>3</sub> : 327°/42° n=61  L <sub>3</sub> : 041°/14° n=59
Distribution of Folds	very few hinges exposed	moderately common	common
Metamorphism	lower greenschist facies: chlorite and sericite growth along S <sub>1</sub>		

\* n = number of readings

\*\* K = Kamb plot

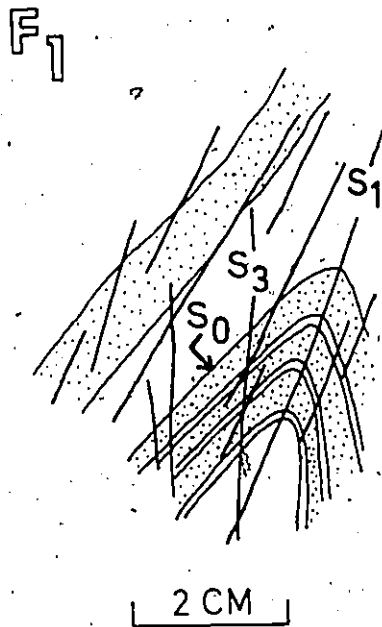


Fig. 10  $F_1$  fold profile

Plan view of phyllitic (not shaded) and quartzose (stippled) beds defining an  $F_1$  fold; unit A2, Ascot Formation (loc. 321).  $S_1$  axial plane foliation formed by aligned sericite.  $S_3$  crenulation and fracture cleavage cuts obliquely across the fold.

which is axial planar to the  $F_1$  folds, is parallel to the bedding, except in the hinge areas, indicating that the  $F_1$  folds are isoclinal.

From Table 10 Appendix I it can be seen that the 14 folded layers measured in 5 folds form modified parallel 1C folds (Ramsay, 1967 p. 365). Thus these  $F_1$  folds appear to be flattened buckle folds (Ramsay, 1967 p. 411-413).

$S_1$  Foliation: The presence of a well developed foliation,  $S_1$ , (Plates IV and VIIIa) is a more widespread evidence of  $D_1$  deformation in the Ascot Formation than are the few  $F_1$  fold closures.

$S_1$  foliation is recognized in the field as regularly spaced planes of parting nearly everywhere parallel to the bedding. The spacing is dependent on the rock type, being very close (1 mm or less) in the phyllites, where it is a well defined schistosity, and from several mm to several cm apart in siltstones and tuffs where it is a fracture cleavage. Some very coarse grained massive beds, about a metre in thickness, of metagraywacke do not exhibit  $S_1$  cleavage.

Microscopically  $S_1$  is defined by the alignment, throughout the phyllosilicate rich rock, of sericite and chlorite and by the elongation of quartz grains. In coarse grained rocks  $S_1$  occurs as an anastomosing foliation (Spry, 1969 p. 208).

In the northern part of the area, the modal average of  $S_1$  foliation planes, measured at 29 localities, predominantly from exposures along and near highway 55, is from the Schmidt

plot\*  $131^{\circ}/70^{\circ}$  (Fig. 25a Appendix II) and  $135^{\circ}/58^{\circ}$  from the Kamb plot\*. In the south, also mainly from outcrops along and near highway 55, the Schmidt modal average of  $S_1$  foliation planes measured at 45 localities is  $330^{\circ}/74^{\circ}$  (Fig. 25a Appendix II). The possible significance of the change in dip of  $S_1$  is considered in a later section (p. 72-74).

In the area of the Stoke Mountains mapped by Lamarche (1965), the southern part of which is included in the present study area, the  $S_1$  modal average of 1,000 measurements is given as  $134^{\circ}/57^{\circ}$  (Lamarche, 1965 p. 185), an orientation statistically identical to that obtained from the Kamb plot of the much smaller sample ( $n=29$ ) in the present study. Evidently the small sample is representative of the population.

$L_1$  Lineations:  $L_1$  lineations that are parallel to  $F_1$  fold axes are relatively common throughout the Ascot Formation. The lineations are formed by the intersection of bedding,  $S_0$ , and foliation,  $S_1$ , and generally recognized as a colour banding on  $S_1$  foliation planes.

The original orientation of the  $F_1$  fold axes is difficult to determine due to the effects of subsequent periods of deformation. On the basis of axial  $L_1$  lineations measured at 30 locations it can be seen (Fig. 25a Appendix II) that most of the  $F_1$  folds now plunge northeast  $50^{\circ}$ - $60^{\circ}$ , however a few

\* See Appendix II for the characteristics of the Kamb and Schmidt methods of contouring orientation data on equal area nets.

plunge gently to the southwest.

## D<sub>2</sub> Deformation

F<sub>2</sub> Folds: Steep to moderately plunging small-scale tight folds affect bedding, S<sub>0</sub>, S<sub>1</sub> cleavage planes, and parallel quartz veins (Plates V and VI; Figs. 11a and 11b) therefore they must be younger than the F<sub>1</sub> folds.

As shown in Table 10 (Appendix I), of the 28 layers and veins measured in 9 folds, 26 are quartz veins, one is a siltstone layer and the remaining layer is siliceous phyllite. Though the number measured is limited, it is evident that, as with F<sub>1</sub> structures, modified (flattened) parallel folds (class 1C) are common (13 quartz veins), but in contrast to F<sub>1</sub> there are also many parallel (class 1B) folds (9 quartz veins, 1 siltstone and 1 phyllite layer) that formed by buckling with little imposed flattening (Ramsay, 1967 p. 411-413).

S<sub>2</sub> Cleavage: A crenulation or fracture cleavage, S<sub>2</sub>, axial planar to F<sub>2</sub> folds is recognized only in the F<sub>2</sub> hinge areas cutting S<sub>1</sub> foliation and parallel bedding. S<sub>2</sub> cleavage is poorly developed, discontinuous, and it occurs at irregularly spaced intervals. It may however be parallel to S<sub>1</sub> foliation on the limbs of isoclinal F<sub>2</sub> folds and thus not apparent. This has also been suggested by Lamarche (1972a p. 13 and oral communication, 1972).

An insufficient number of S<sub>2</sub> cleavage planes were observed to give a significant modal average, however those measured (19) in the southwestern part of the area dip steeply to the

F<sub>2</sub>

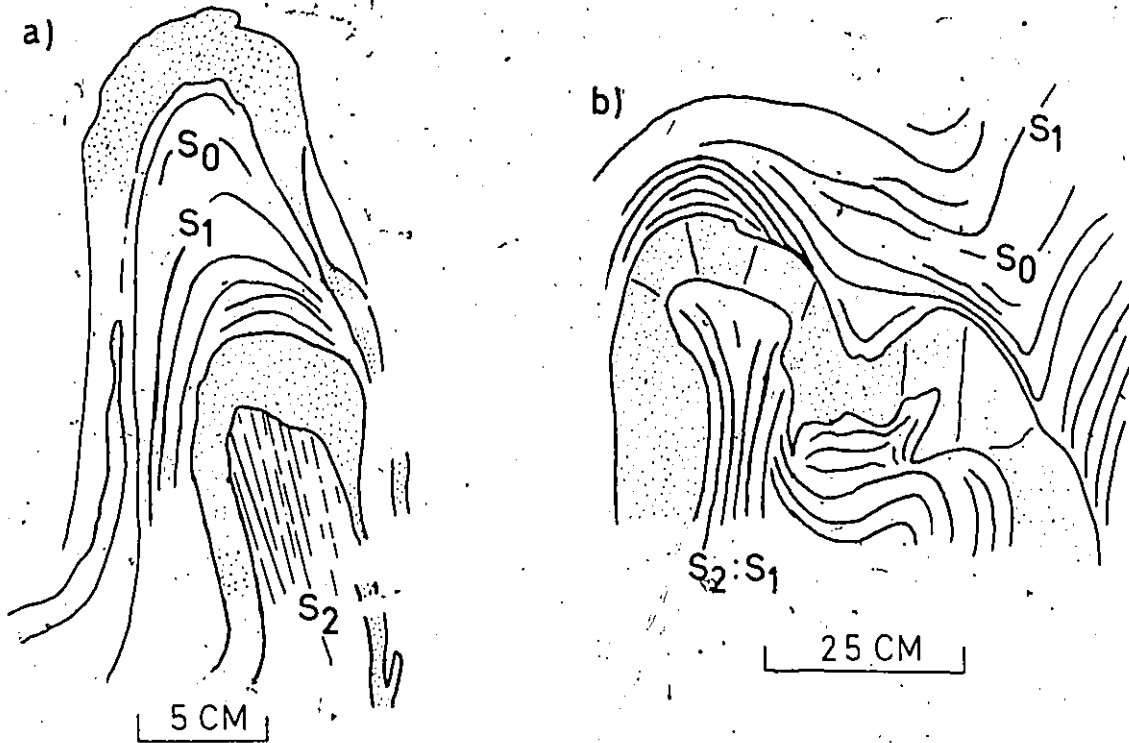


Fig. 11a F<sub>2</sub> fold profiles

a) Quartz vein (stippled) and parallel S<sub>1</sub> foliation and S<sub>0</sub> (bedding) define an F<sub>2</sub> fold in phyllite; unit A4, Ascot Formation (loc. 71).

b) F<sub>2</sub> fold defined by a quartz vein (stippled) in S<sub>1</sub> cleavage plane (parallel to bedding, S<sub>0</sub>); phyllitic rock; unit A4, Ascot Formation (loc. 69, see also Plate Vb).

F<sub>2</sub>

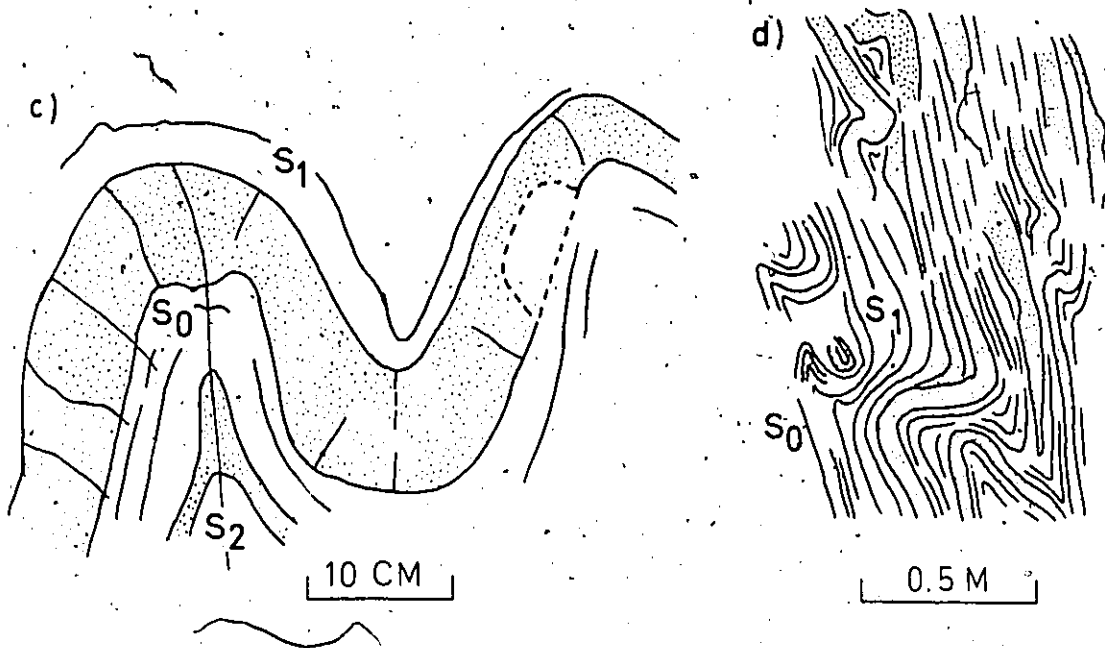


Fig 11b F<sub>2</sub> fold profiles

- c) F<sub>2</sub> folds in quartz veins (stippled) and parallel bedding, S<sub>0</sub>, and foliation, S<sub>1</sub>, in phyllite (unshaded); unit A4, Ascot Formation (loc. 71). S<sub>2</sub> is a fracture cleavage.
- d) F<sub>2</sub> folds in quartz veins (stippled) and parallel S<sub>1</sub> foliation in a phyllitic rock; unit A4, Ascot Formation (loc. 71, see also Plate VIa).

northwest, as does the  $S_1$  foliation. No  $S_2$  cleavage planes were observed in the northern part of the area where  $S_1$  foliations dip to the southeast but it is suggested that if they are present they dip to the southeast.

$L_2$  Lineations: Lineations parallel to the axes of  $F_2$  folds are formed by the intersection of  $S_1$  and  $S_2$  cleavages and they are recognized as very fine striations which are generally only seen on the  $F_2$  hinges and in the phyllitic rocks. As shown in Fig. 25a (Appendix II), the lineations which are parallel to the axes of the  $F_2$  folds, on a Schmidt modal average, plunge  $56^\circ$  to  $044^\circ$ . That is closely parallel to the Kamb modal average of  $L_1$  lineations ( $041^\circ/54^\circ$ ). Evidently  $F_1$  and  $F_2$  folds are nearly coaxial.

### $D_3$ Deformation

$F_3$  Folds:  $F_3$  folds are more commonly exposed than  $F_1$  or  $F_2$ . They vary in size from crenulations and microscopic folds to those more commonly about a metre in wavelength (Fig. 12 and Plates VII, VIII, IX and X). Most have interlimb angles of approximately  $40^\circ$ - $120^\circ$ . Since the  $F_3$  folds affect  $S_0$  (bedding) and parallel  $S_1$ ;  $S_2$  cleavages they must be younger than the  $F_2$  folds.

In quartz-rich pelites 19 of the 23 layers measured in 7 folds (Table 10, Appendix I) form class 1C (modified parallel) folds. The dominance of 1C folds indicates that, as with  $F_1$ , and to a lesser extent  $F_2$  folds, an important mechanism of folding was buckling accompanied or followed by flattening

F<sub>3</sub>

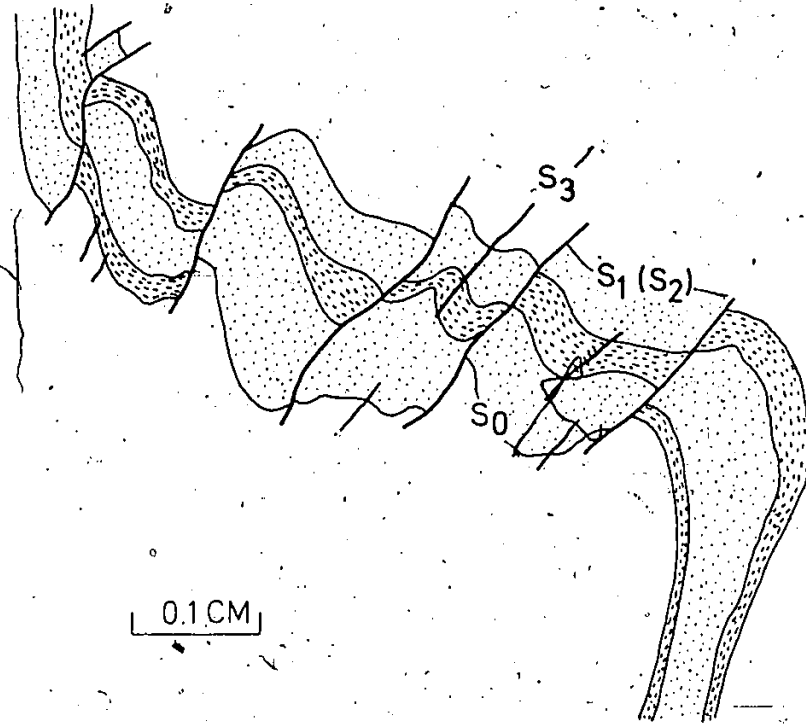


Fig. 12 F<sub>3</sub> crenulations and slip cleavage

Schematic profile of F<sub>3</sub> crenulations in micaceous pelitic (dashed) layers and quartz-rich pelitic (stippled) layers and parallel S<sub>1</sub> (S<sub>2</sub>) cleavages; unit A4, Ascot Formation (loc. 317, see also Plate VIIIb). Slip cleavage, S<sub>3</sub>, offsetting layering is axial planar to the crenulations. S<sub>3</sub> cleavage generally makes an angle of approximately 40° with S<sub>1</sub> (S<sub>2</sub>) cleavages.

(Ramsay, 1967 p. 411-413) ("flexural flow" of Donath and Parker, 1964).

S<sub>3</sub> Cleavage: S<sub>3</sub> is prominent throughout the Ascot Formation as a crenulation cleavage, often at a high angle to bedding, which has in some localities developed into a slip cleavage that exhibits offsets of the layering (Fig. 12 and Plates VII to IX). S<sub>3</sub> is also recognized as a fracture cleavage where S<sub>1</sub> and S<sub>2</sub> are locally absent.

The spacing of the planes of parting mesoscopically defining the S<sub>3</sub> cleavage varies from a few millimetres in phyllites to several centimetres in the fine grained sandstones and tuffs to irregular in coarse sandstones.

Microscopically, S<sub>3</sub> is expressed as regularly spaced crenulations, especially in the pelitic rocks (Plate VIIb), and in metavolcanics and siltstones as discontinuous crenulations and fractures. Quartz grains are fractured and exhibit undulose extinction.

S<sub>3</sub> cleavages dip northwest throughout the area at 30° to 60° and the Schmidt modal average of 61 measurements is 327°/42°, (Fig. 25a Appendix II); that is, S<sub>3</sub> is generally less steep than S<sub>0</sub>, S<sub>1</sub> or S<sub>2</sub>. Unlike S<sub>1</sub> and S<sub>2</sub>, there is no apparent change in dip from the northern to the southwestern part of the outcrop area of the Ascot Formation. The significance of this arrangement in relation to major structures is discussed later (p. 72-74).

L<sub>3</sub> Lineations: Axial lineations are formed by the hinges of

small scale folds and crenulations of  $S_1/S_2$  foliation planes. Where  $S_1$  and  $S_2$  foliations are locally absent,  $L_3$  also occurs as colour bands on  $S_3$  due to the intersection with bedding ( $S_0$ ).

The Schmidt modal value of 59  $L_3$  lineation measurements plunges northeast at  $14^\circ$  towards  $041^\circ$  (Fig. 25a Appendix II). Some  $L_3$  lineations, particularly in the southern part of the area, plunge southwest from  $0^\circ$  to  $15^\circ$ , and in several outcrops  $L_3$  plunge gently both northeast and southwest, suggesting that larger folds are doubly plunging.

#### Metamorphism

Abundant sericite and a lesser amount of chlorite aligned along the  $S_1$  foliation planes indicates that during or following  $D_1$  deformation rocks of the Ascot Formation were metamorphosed to the lower greenschist facies. Sericite flakes observed along the  $S_2$  and  $S_3$  cleavages may be syntectonic with  $D_2$  and  $D_3$  deformations (see also Lamarche, 1965).

Chlorite, derived from biotite, is common in the albite granitic rocks; it probably developed during the younger (Acadian) phases of deformation thus updating the radiogenic age dates (see also "Albite Granite" Chapter II).

For a more detailed account of the metamorphism in the Ascot Formation, including various mineral assemblages and chemical equations, see Lamarché (1965).

St. Francis Group

Microscopic to large scale structures attributable to two phases of deformation are present in most localities in rocks of the St. Francis Group. Additionally there are locally developed later crenulations. The main characteristics of the structures are summarized in Table 6.

DD<sub>1</sub> Deformation

FF<sub>1</sub> Folds: Microscopic and mesoscopic isoclinal folds

(affecting only one layer), as well as folds affecting several layers are present, though hinges are exposed in only a few areas. The largest FF<sub>1</sub> folds observed are in a road cut about 1 mile (1.6 km) east of Compton (Fig. 1 and Plate XIII) and these approximate 30 metres in wavelength. The FF<sub>1</sub> folds generally have an axial-plane cleavage, SS<sub>1</sub>, closely parallel to the bedding on the fold limbs (Plates XI, XII, XIV and Fig. 13) however SS<sub>1</sub> cuts obliquely across the fold limbs in some localities (Plate XIII and Fig. 14).

Of the 4 folds measured in detail (Table 11 Appendix I) 15 limestone layers and 5 calcareous siltstone and slate layers form class 1C folds and 15 calcareous micaceous siltstone layers form class 2 (similar) folds. The shapes indicate a buckling and flattening mechanism for the folds in the limestones and calcareous siltstones whereas the class 2 (similar) folds in the calcareous micaceous siltstone layers may have formed by differential slip across the layers in response to buckling in adjacent more competent layers.

Table 6 Characteristics of Structures: St. Francis Group  
(Devonian and Upper and Middle Silurian)

Phases of Deformation	DD <sub>1</sub>	DD <sub>2</sub>
Folds	FF <sub>1</sub>	FF <sub>2</sub>
Folded Surface	SS <sub>0</sub> (bedding)	SS <sub>0</sub> ; SS <sub>1</sub>
Shape and Approximate Interlimb Angles	intrafolial - tight to isoclinal 0°-30°	close - open 60°-120°
Ramsay's (1967) Class	1C; 2	1B; 1C; 2
Observed Scale	micro - meso - macro (?)	meso - macro
Axial Plane Cleavage	SS <sub>1</sub> : penetrative slaty cleavage and schistosity	SS <sub>2</sub> : crenulation cleavage with offsets; fracture and slaty cleavage
Axial Lineation	LL <sub>1</sub> : colour banding due to SS <sub>1</sub> /SS <sub>0</sub> intersection	LL <sub>2</sub> : crenulations and colour banding due to SS <sub>1</sub> /SS <sub>2</sub> and SS <sub>0</sub> /SS <sub>2</sub> intersections
Orientation (modal values)	SS <sub>1</sub> : (K*) 313°/65° n=132 309°/43°; 315°/81° n=132	SS <sub>2</sub> : 316°/37° n**=178
Distribution of Folds	LL <sub>1</sub> : 050°/49°; 015°/46° n=53	LL <sub>2</sub> : 008°/23°; 045°/14° n=163
Metamorphism	very few hinges exposed	common
	sericite (muscovite) growth on S <sub>1</sub>	

K = Kamb plot

\*\* n = number of readings

FF<sub>1</sub>

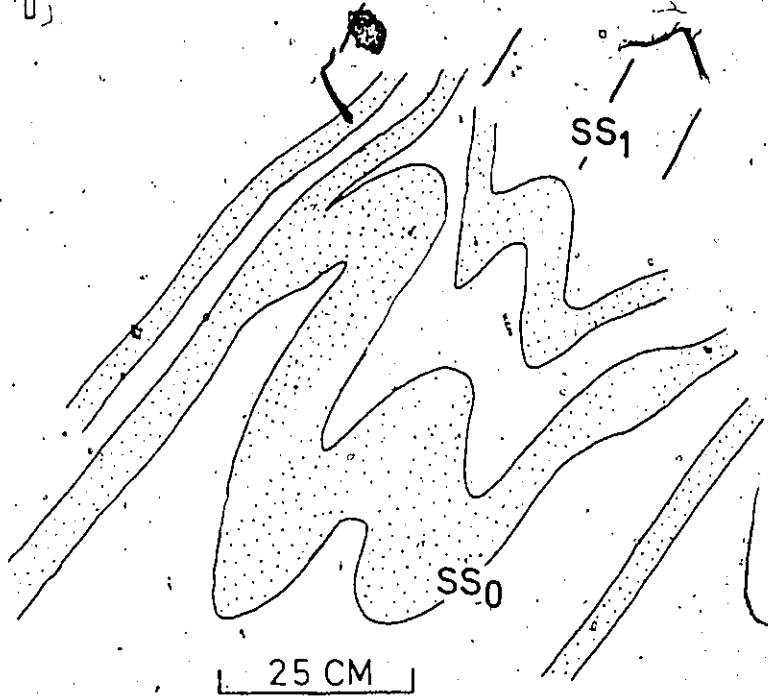


Fig. 13 FF<sub>1</sub> fold profile

Intrafolial folds defined by a quartz-mica rich bed (stippled) in siliceous limestone (unshaded); unit F2, Ayer's Cliff Member, St. Francis Group (loc. 53, see also Plate XIa). In the fold limbs SS<sub>1</sub> slaty cleavage is parallel to the bedding, SS<sub>0</sub>.

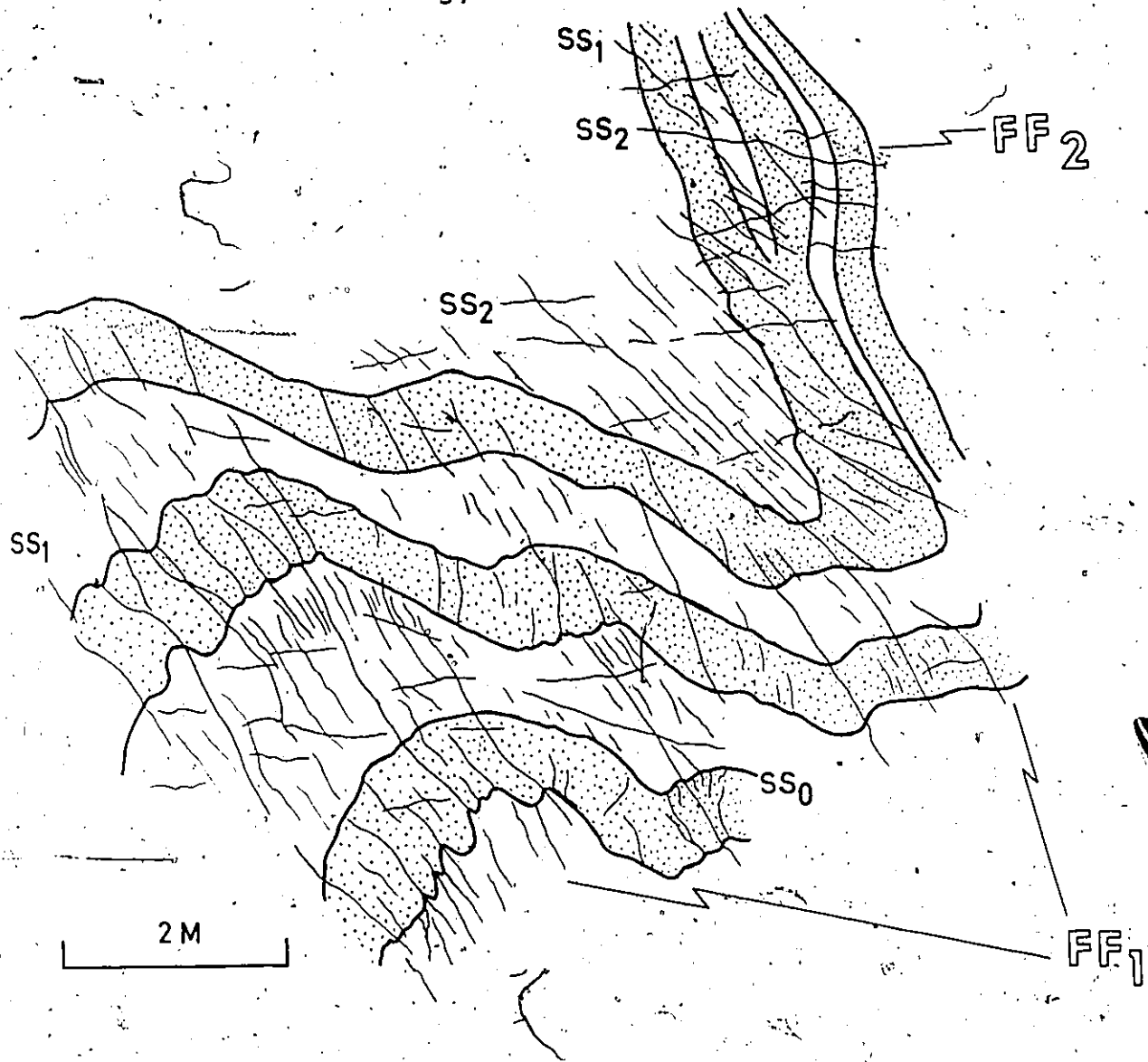


Fig. 14  $FF_1$  and  $FF_2$ , fold profiles and foliations

Quartz-siltstone layers are stippled and calcareous siltstone and slate layers are blank; Westmore Member, St. Francis Group (loc. 185, see Plate XIIIa). An irregular  $SS_2$  fracture and crenulation cleavage crosses the  $FF_1$  folds.

("passive folding" of Donath and Parker, 1964).

In the hinge zone of one of the large folds well exposed in the road cut 1 mile (1.6 km) east of Compton (Fig. 1), there are well developed mullion-like structures on the lower surface of a quartz siltstone bed underlain by calcareous silty slate (Plate XIIIb). The "mullions" are separated by cusps of the slate that protrude upward as much as 20 cm parallel to the  $SS_1$  cleavage. Possibly the structures developed during deformation by intrusion of relatively mobile argillaceous material into the quartz siltstone. Alternatively the "mullions" may be large flame casts that during deformation were re-oriented parallel to  $SS_1$ .

$SS_1$  Cleavage: In slates, phyllites and limestones,  $SS_1$  cleavage is very prominent, for the most part parallel to the bedding on the limbs of isoclinal  $FF_1$  folds (Plate XXa). In limestones the cleavage parting planes as observed in the field are about 1 mm to several cm apart. The spacing in slates and phyllites is more consistently of the order of a millimetre, whereas in massive dolomite layers (each about a metre in thickness) the cleavage is not apparent. In silty and sandy layers, which occur in the eastern part of the study area, in the Westmore Member, the spacing is irregular, and in some beds the cleavage is not apparent. The  $SS_1$  cleavage is normal to the short axis of tectonic (?) "boulders" found in the Barton River Member, which may indicate flattening across the cleavage and stretching during folding to cause separate boudins to form from a continuous layer (Fig. 15).

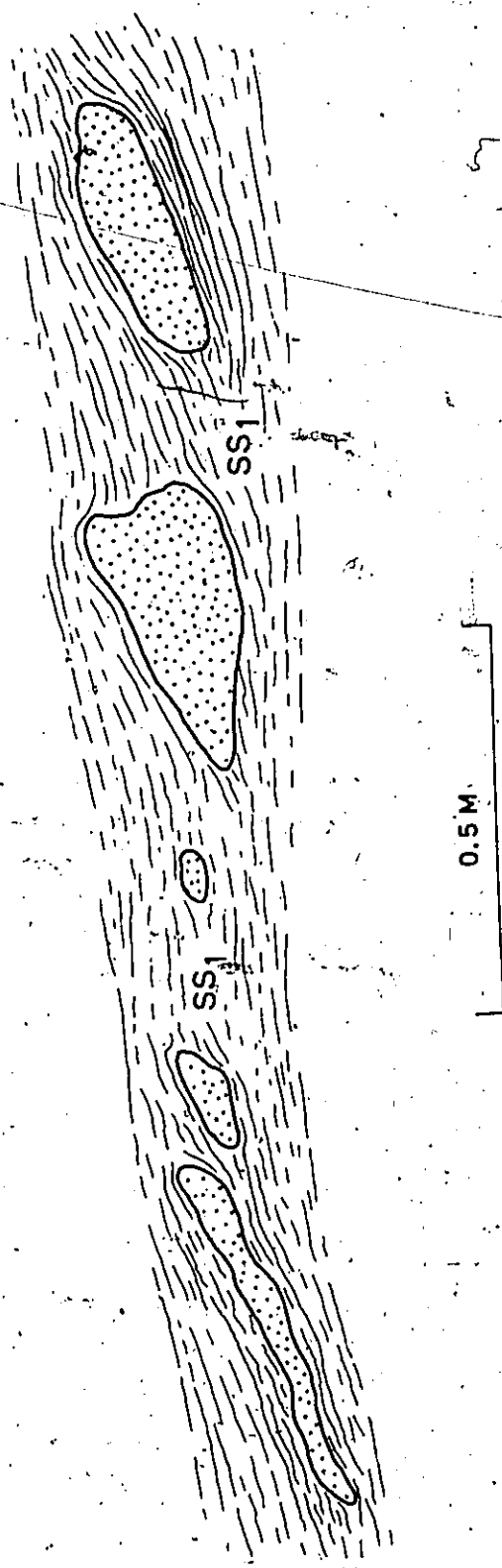


Fig. 15 Tectonic "boulders" in the SS<sub>1</sub> plane. The calcareous quartz siltstone "boulders" (stippled) are elongated such that their long axis lies in the plane of SS<sub>1</sub> in the surrounding calcaeous slate (unshaded). Barton River-Member, St. Francis Group, map unit F3 (loc. 216).

Microscopically the  $SS_1$  cleavage is defined by the alignment of elongated calcite and quartz grains and by the alignment of a very minor amount of sericite. The  $SS_1$  cleavage is frequently anastomosing (Spry, 1969 p. 208), especially in the quartz siltstones and sandstones (Plate XVIII).

During the field investigation it first appeared that structures attributed to the first phase of deformation were absent to the east. However a reconnaissance study revealed that a cleavage parallel to bedding, which may be equivalent to  $SS_1$ , is present at least as far east as St-Zacharie (Fig. 3) about 100 miles (160 km) east of the study area. One of the localities in which  $FF_1$  folds are best exposed (Plate XIVa) lies about 15 miles (24 km) to the east of the study area, 0.5 miles (0.8 km) south of St. Hermenegilde on the road to Villette (Fig. 3).

The Schmidt plot of  $SS_1$  cleavages measured at 132 locations (Fig. 25b Appendix II) shows that  $SS_1$  dips variably northwest, with modal concentrations at both  $309^\circ/43^\circ$  and  $315^\circ/81^\circ$ . This might suggest subdomains with different modes, as for  $S_1$  in the Ascot Formation, however the localities where  $SS_1$  cleavage approximates these modes appear to be randomly distributed throughout the area. The Kamb plot (Fig. 25b Appendix II) gives a single mode ( $313^\circ/65^\circ$ ), which could indicate that the sample is from a unimodal population. Nevertheless, there are some marked local changes in dip, and these may be related to large scale  $FF_2$  or older folds.

LL<sub>1</sub> Lineations: LL<sub>1</sub> lineations parallel to FF<sub>1</sub> fold axes are recognized on the SS<sub>1</sub> cleavage planes as a colour banding and ridges representing the traces of bedding (Plates XV and XVII). In several localities a "stretch" lineation formed by elongated pyrite aggregates is parallel to LL<sub>1</sub> suggesting that extension of the layering along the fold axis took place during DD<sub>1</sub> deformation.

Most LL<sub>1</sub> lineations plunge moderately to steeply north northeasterly with modal Schmidt values for the 53 measurements of 46° towards 015° and 49° towards 050° (Fig. 25b Appendix II).

Near the Stoke Mountain complex (Ascot Formation) LL<sub>1</sub> tends to plunge more steeply than it does further east. As shown graphically (Fig. 16b), although plunges vary considerably throughout the area, within 3 miles (4.8 km) of the complex (that is with few exceptions in limestones of the Ayer's Cliff Member) there is a general increase in plunge as the complex is approached. The SS<sub>1</sub> planes on which LL<sub>1</sub> lie are fairly consistent in strike and the dips also generally increase (Fig. 16a). The increase in plunge and dip might suggest that as the complex is approached the fold axes tend to rotate towards a steep direction of extension, due perhaps to the complex acting as a rigid buttress during deformation (see also Divi and Fyson, 1973). However, the rake of LL<sub>1</sub> on SS<sub>1</sub> does not appreciably increase (Fig. 16c) indicating that the change in plunge is predominantly a function of the dip of SS<sub>1</sub>. Why the dip changes is not clear. To test whether or not there is a change in strain towards the complex it will be necessary to measure strain markers, such as pebbles.

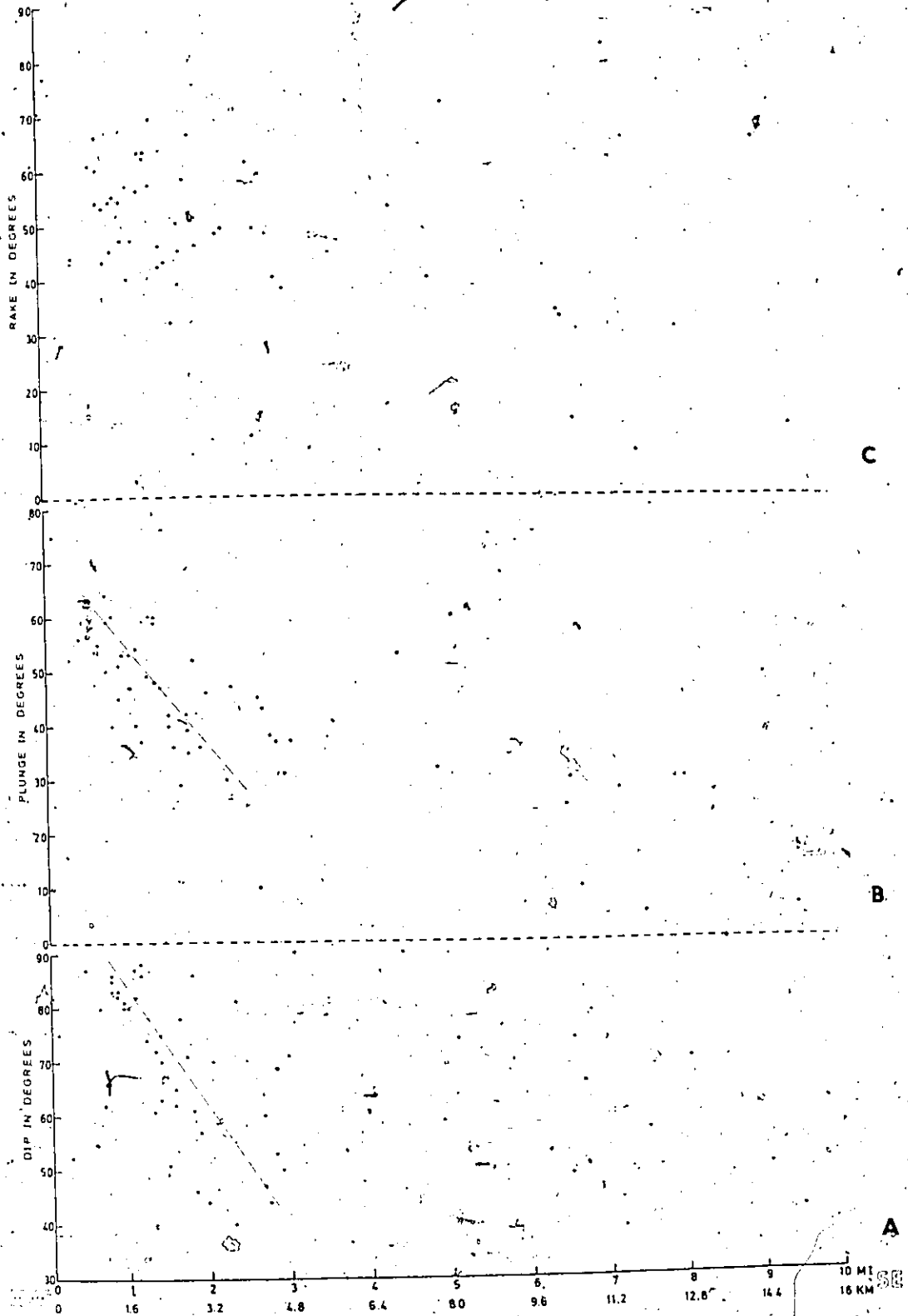


Fig. 16 Graph comparing steepness of  $F_{E1}$  fold structures in the St. Francis Group with distance southeast of the Stoke Mountain complex. A) dip of  $SS_1$  cleavage, B) plunge of  $LL_1$  lineation, and C) rake of  $LL_1$  on  $SS_1$ .

DD<sub>2</sub> Deformation

FF<sub>2</sub> Folds: The most obvious folds in the St. Francis Group affect the bedding and SS<sub>1</sub> cleavage (Fig. 17 and Plate XIX) and thus are obviously younger than the FF<sub>1</sub> folds. The FF<sub>2</sub> folds are open to close with limbs less than a metre to over 10 metres in length, that is some folds are larger than single outcrops. The small scale (mesoscopic) folds are not continuous and can be considered as lying in pairs with bedding and SS<sub>1</sub> in a short common limb rotated northwest towards the horizontal. Thus when viewed northward, the fold pair is "S" shaped (Fig. 6 cross-sections). The relationship of the fold pairs to major folds is considered in a later section (p. 75).

Of the 44 layers measured in 11 folds (Table 11, Appendix I), 18 limestone layers form class 1B (parallel) folds, 12 calcareous siltstone, silty limestone, limestone, and siltstone layers form class 1C folds, and 14 siliceous limestone and argillite layers form class 3 folds where the curvature of the outer surface is greater than the inner. Evidently the limestone beds were deformed mainly by buckling, the silty limestone beds by buckling and flattening, and the siliceous limestones and argillites tended to accommodate to the spaces between these relatively competent beds.

SS<sub>2</sub> Cleavage: A cleavage, SS<sub>2</sub>, which lies approximately parallel to the axial surfaces of the FF<sub>2</sub> folds is prominent in many outcrops (Plates XVI, XIX and XX). It is usually in the form of a crenulation of SS<sub>1</sub>, however where SS<sub>1</sub> is absent

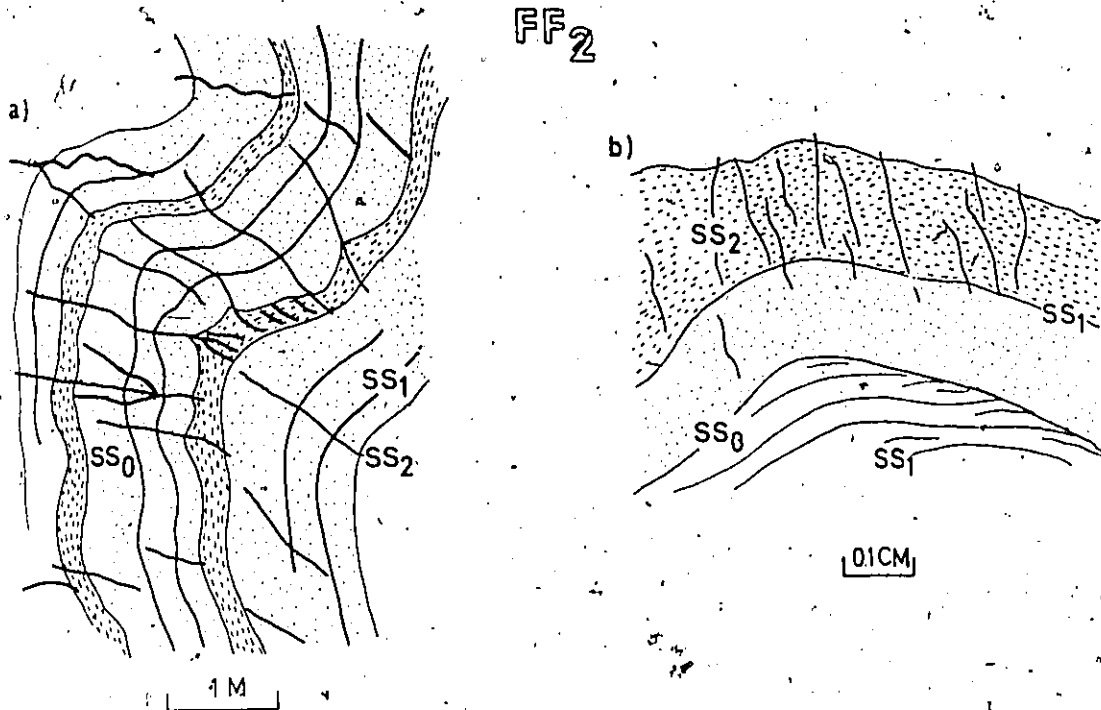


Fig. 17 FF<sub>2</sub> fold profiles

a) Folded siliceous limestone (stippled) and calcareous phyllite (dashed) beds (SS<sub>0</sub>) and parallel SS<sub>1</sub> cleavage; unit F2, Ayer's Cliff Member, St. Francis Group (loc. 34, see also Plate XIXa). SS<sub>2</sub> crenulation cleavage is axial planar to the folds and generally forms an angle of about 40° with bedding (SS<sub>0</sub>) and parallel SS<sub>1</sub> cleavage.

b) Hinge area of an open fold in calcareous phyllite (dashed) and calcareous siltstone (stippled) beds (SS<sub>0</sub>) and SS<sub>1</sub> cleavage; unit F3, Barton River Member, St. Francis Group (loc. 205, see also Plate XIXb). SS<sub>2</sub> cleavage is present as discontinuous crenulations and fractures.

it is also present as a fracture cleavage,  $SS_2$  is poorly developed or absent in coarse grained sandstones (Plate XVIa).

In most places limestone, calcareous sandstone, and silty sandstone beds are crossed by  $SS_2$  parting planes that are several centimetres apart. In slates and phyllites the planes are closer than a millimetre.

$SS_2$  is recognized microscopically in the coarser grained calcareous and quartz-rich rocks as discontinuous crenulations and fractures (Plate XIXb) and in the phyllitic rocks as a penetrative crenulation cleavage (Plate XXb) that sometimes offsets the layering and  $SS_1$  to form a slip-cleavage.

The modal average (Schmidt projection) of 178  $SS_2$  planes measured dips  $37^\circ$  towards  $316^\circ$  (Fig. 25b Appendix II). The average angular relationship with the more steeply inclined  $SS_1$  cleavage (which is closely parallel to  $SS_0$ ) is consistent with the "S" shape of the  $F_2$  fold pairs.

LL<sub>2</sub> Lineations:  $LL_2$  lineations are the most widespread lineations in rocks of the St. Francis Group (Plate XVII). They are most pronounced as axes of crenulations of  $SS_1$  cleavage in thin phyllitic layers.

Most  $LL_2$  lineations plunge northeast to north-northeast at less than  $35^\circ$ . Both the Kamb and Schmidt projections of 163 measurements of  $LL_2$  (Fig. 25b Appendix II) indicate that the  $LL_2$  lineations have two modes (Schmidt  $008^\circ/23^\circ$  and  $045^\circ/14^\circ$ ). The  $\beta$  intersection of one of the two Schmidt modes of  $SS_1$  ( $309^\circ/43^\circ$ ) with the single mode  $SS_2$  ( $290^\circ/37^\circ$ ) is within four degrees of the  $LL_2$  mode of  $008^\circ/23^\circ$ . Similarly

the  $\beta$  intersection of the other Schmidt mode of  $SS_1$  ( $315^\circ/81^\circ$ ) and  $SS_2$  is close to the  $LL_2$  mode of  $045^\circ/14^\circ$ . Evidently due to the two modal  $SS_1$  surfaces there are two corresponding modes of  $LL_2$  on these surfaces.

### DD<sub>3</sub> Deformation

Structures attributable to  $DD_3$  deformation were noted to be common in one area, about 2 miles (3.2 km) north of the International Border on highway 55, near a small granitic pluton in the St. Francis Group. No  $FF_3$  folds larger than crenulations were observed. Crenulations that affect  $SS_1$  cleavage and cross  $FF_2$  folds obliquely are present in a few other localities; on the map (Fig. 6; in pocket) they are grouped as  $DD_3$  structures.

SS<sub>3</sub> Cleavage:  $SS_3$  cleavage occurs as a crenulation cleavage (Plate XXIIa) evenly spaced about a centimetre apart where it is present in proximity to the granitic pluton. It dips steeply northwest and southeast.

LL<sub>3</sub> Lineations:  $LL_3$  lineations near the granite are pronounced crenulation axes on  $SS_1$  cleavage (Plate XXIIa) that plunge variably to the southwest and northeast. Elsewhere the lineation occurs as a very fine crenulation.

### Metamorphism

The only evidence recognized for growth of new minerals during  $DD_1$  deformation is the presence of a few sericite and

muscovite flakes aligned along  $SS_1$  cleavage planes. No such minerals were observed aligned along  $SS_2$  or  $SS_3$  cleavages, hence metamorphism during  $DD_2$  and  $DD_3$  deformation appears to have been minimal.

The presence of calcite in pressure shadows (Spry, 1969 p. 240-244) parallel to  $SS_1$  (Plate XXIb) indicates calcite growth during  $DD_1$  deformation. Triple junctions in quartz aggregates around which  $SS_1$  cleavage is deflected (Plate XXIIa) are evidence for the extensive recrystallization after  $DD_1$  deformation.

Near the granitic plutons (Fig. 5), random post-deformational mineral grains include large metasysts of biotite (Plate XXIIb), a considerable amount of sericite and pyrite, a minor amount of epidote and chlorite, and a few small tourmaline crystals. Evidently the mineral growth is the result of contact metamorphism (see also Albee, 1968).

In New England regional metamorphism accompanied folding of Siluro-Devonian rocks and in the southwestern part it is indistinguishable from the metamorphic effects of the granite plutons (Thompson and Norton, 1968). In northeastern Vermont (as in the study area) the presence of well defined aureoles around the granites suggests shallow emplacement (see also Doll, 1961).

#### Magog Group

#### Beauceville and Sherbrooke Formations

Only a few outcrops were examined in the Middle Ordovician

slates and siltstones of the Beauceville Formation (Fig. 4), part of which outcrops in the northwestern corner of the study area (Fig. 5). Structures attributable to two phases of deformation (here termed MD<sub>1</sub> and MD<sub>2</sub>) were observed by St-Julien (1963b) in both the Beauceville and overlying Upper Ordovician Sherbrooke Formations. Minor amounts of syntectonic metamorphic minerals (mainly sericite) are associated with the cleavages. St-Julien (1963b) also described a cleavage attributable to a third phase of deformation in the southwestern part of the Beauceville Formation.

The characteristics of these deformational phases, mainly obtained from St-Julien (1963b) are shown in Table 7 and on the modal average map (Fig. 8) and accompanying cross sections (Fig. 9).

Unlike structures in the Ascot Formation, or St. Francis Group, no early intrafolial isoclinal folds are apparent in the Beauceville or Sherbrooke Formations. The first phase foliation, MS<sub>1</sub>, is a slaty or fracture cleavage, commonly at an appreciable angle to bedding. MS<sub>1</sub> strikes northeast and dips near vertically. An axial lineation, ML<sub>1</sub>, plunges gently to moderately northeast. MS<sub>1</sub> is crossed by MS<sub>2</sub> crenulation cleavage dipping moderately northwest. The modal orientation of MS<sub>2</sub> (322°/53°) obtained by St-Julien (1963b) is identical to that of S<sub>3</sub> (S<sub>2</sub>) obtained by Lamarche (1965) for the Ascot Formation to the southeast (Table 5). Axial lineations of both phases affecting the Magog Group (ML<sub>1</sub> and ML<sub>2</sub>) plunge gently to moderately northeast.

Table 7 Characteristics of Structures: Magog Group; Beauceville and Sherbrooke Formations (Middle to Upper Ordovician) (from St-Julien, 1963b)

Phase of Deformation	MD <sub>1</sub>	MD <sub>2</sub>
Fold Scale	micro (?) - meso - macro	micro (?) - meso - macro (?)
Axial Plane Cleavage	MS <sub>1</sub> : slaty to fracture cleavage	MS <sub>2</sub> : crenulation cleavage
Axial Lineation	ML <sub>1</sub> : colour bands due to trace of bedding on MS <sub>1</sub>	ML <sub>2</sub> : crenulations of MS <sub>1</sub> around MS <sub>2</sub>
Orientation (modal values)	MS <sub>1</sub> : 117°/78° n*=1700 ML <sub>1</sub> : 034°/29° n=400	MS <sub>2</sub> : 322°/53° n=300 ML <sub>2</sub> : 039°/20° n=200
Intensity of Deformation	penetrative	penetrative
Metamorphism	sericite growth only	

Cleavages attributable to a third phase of deformation are present in the southern part of the Beauceville Formation (St-Julien, 1963b).

\* n = sample size

## Glenbrooke Group

A brief reconnaissance survey of the limestones and slates of the Glenbrooke Group about 4 miles (6.4 km) south of Sargent Bay (Fig. 4) indicated the presence of structures attributable to only one phase of deformation (Table 8) in which a steep fracture or slaty cleavage,  $GS_1$ , lies oblique to the bedding (Plate XXIII). Elsewhere within these rocks the structures appear to be similar (Drapeau, 1961).

## Relationship Between Small Scale and Major Structures

Stoke Mountain Complex: Ascot Formation

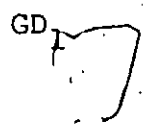
Major  $F_1$  folds indicated by Lamarche (1972a) as having northerly striking axial surfaces are not readily geometrically related to the small scale  $F_1$  isoclinal folds observed in the Ascot Formation.

The two northwest overturned major folds, the Eustis and Sherbrooke anticlines (Fig. 6; in pocket) mapped by St-Julien and Lamarche (1965) on the basis of top determinations (pillows), stratigraphic repetition and minor folds, may be steeply plunging  $F_2$  major folds as suggested by Lamarche (1972a). However, exposures around the fold closures are rare and it was not possible to determine whether or not  $S_1$  cleavage follows around the hinges and is crossed by  $S_2$  cleavage.

On the basis of the shape of minor folds, St-Julien and Lamarche (1965) considered the Sherbrooke anticline to be

Table 8 Characteristics of Structures: Glenbrooke Group (Upper Silurian; Drapeau, 1961)

Phase of Deformation



Scale

micro (?) - meso - macro

Axial Plane Cleavage

GS<sub>1</sub>: slaty to fracture cleavage

Axial Lineation

GL<sub>1</sub>: colour banding due to trace of bedding on S<sub>1</sub>

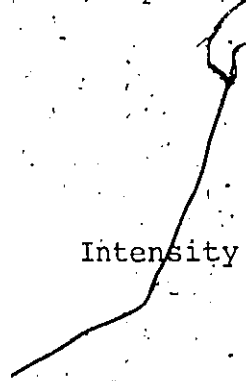
Orientation

(Drapeau, 1961)

GS<sub>1</sub>: 290°/vertical  
110°/vertical

Intensity of Deformation

penetrative



refolded into a large open anticline, possibly  $F_3$ . However a cross section (Fig. 9) based on their map does not indicate the presence of such a structure. Evidence for a major anticlinal axis within the southern part of the Stoke Mountains, indicated by Baer (1961), St-Julien (1967) and Cady (1969 p. 67) (Fig. 2), is also not clear. Certainly the outcrop pattern does not reveal shapes of major folds. Cady (1967) considered the Stoke Mountain complex to be a geanticline (structural high in the orthogeosyncline).

As with the  $FF_2$  folds in the St. Francis Group, throughout the area the mesoscopic and larger  $F_3$  folds when viewed northward can be considered to form "S" type fold pairs (Fig. 6; cross sections). The shapes are as if the folds were parasitic to a major  $F_3$  antiform with an axial zone to the northwest; but the "S" shape symmetry of  $F_3$  and correlative folds ( $MF_2$ , see Table 7) in the Magog Group to the northwest does not change so that the axis is never crossed (Fig. 6).

The change in dip of  $S_1$  from steep southeasterly in the northern part of the area to steep northwesterly in the south (Fig. 6; in pocket) may indicate the presence of a large scale open fold with a low dipping axial surface (Fig. 18). Because the symmetry of the small scale  $F_3$  folds is constant throughout and the axial surfaces are steeper than that of the possible large fold, this is not considered to be an  $F_3$  structure. Also, the intersection of the two modal average  $S_1$  planes plunges northeast more steeply than the modal value for the  $L_3$  lineations (Fig. 25a Appendix II). As  $S_3$  is constant in orientation throughout, the change in dip of  $S_1$  may reflect

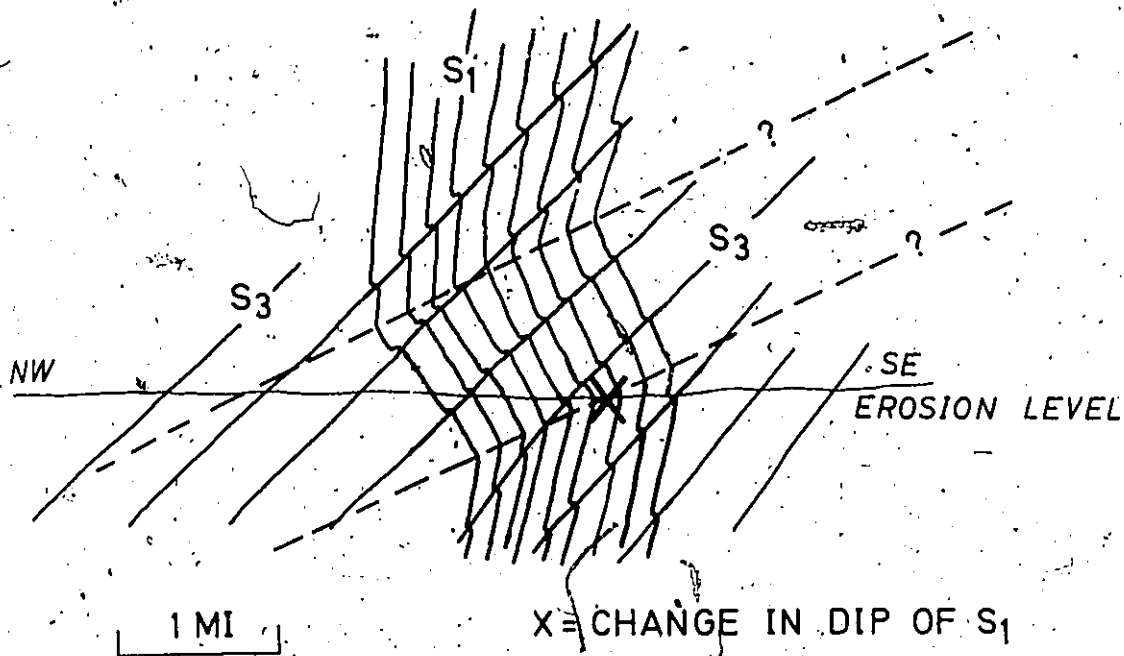


Fig. 18 Diagrammatic sketch of possible large scale folds suggested by changes in dip of  $S_0$  and  $S_1$  (and parallel  $S_2$ ) in the Ascot Formation.

large scale open folding after  $F_2$  but before  $F_3$  folding (cf. the similar relationship in the St. Francis Group with the  $SS_1$  dip changes and  $LL_2$  (p. 74-77)).

The outcrop of the Stoke Mountain complex extends southwest slightly oblique to the various foliations and the line of change in dip of  $S_1$ . Possibly the outcrop pattern is unrelated to either major or minor folds, but rather reflects a horst-like fault block.

#### St. Victor Synclinorium: Magog Group

Axes of large scale folds shown on the map of St-Julien (1970b) have most probably been determined on the basis of the outcrop pattern. In general they plunge northeastward in directions similar to that of the small scale first folds.

The axis to the polar girdle of the  $MS_1$  cleavage planes (St-Julien, 1963b p. 281), that is the fan axis of the axial plane cleavage, coincides with the modal axial lineation  $ML_1$  ( $034^\circ/29^\circ$ ) thus it seems that the minor  $F_1$  folds are geometrically and genetically related to the major folds.

#### Connecticut Valley - Gaspé Synclinorium: St. Francis Group

On the basis of topographic expression (since the exposures are extremely limited) Kerr (1923) indicated a syncline in the St. Francis Group in the Tomifobia River Valley (Figs. 1 and 3). The Indian Point Syncline shown by Doll (1951) in adjacent Vermont is possibly a southern continuation of this structure. However, stratigraphic control is insufficient for unequivocal identification and the rock units are interpreted

in this study (Figs. 6 and 9) as becoming progressively younger eastward in a major monocline; an interpretation modified from that of Cooke (1957 p. 11).

In the St. Francis Group, rock units could not be mapped in sufficient detail to show shapes of large folds and small scale  $FF_1$  folds are not exposed sufficiently to obtain vergence patterns that might indicate larger structures.

As described for the similar "S" shaped  $F_3$  folds in the Ascot Formation, the arrangement of  $FF_2$  small scale folds is as if on a single steep limb, partly overturned southeast, of a major anticline to the northwest and syncline to the southeast (Fig. 6). In the few places where apparent, the stratigraphic tops of steeply dipping beds face southeast in conformity with this arrangement. Cooke (1957 p. 11-12) who did not recognize the earlier  $FF_1$  folds, estimated the stratigraphic thickness of beds on this apparently steep limb to be in excess of 14 miles (22.4 km).

It seems more probable, however, that the  $FF_2$  folds are unrelated to such a structure and that as interpreted in the cross sections of Figs. 6 and 9 there is an enveloping surface dipping gently eastward toward the axial area of the Connecticut Valley - Gaspé synclinorium (see also Cady, 1969 Plate 3).  $FF_1$  folds and bedding-plane faults (not seen) may account for the stratal repetitions necessary to allow local steep dips yet an overall low dip (Fig. 19b).

As previously noted (p. 60)  $SS_1$  dips variably northwest and forms two modes (Fig. 25b, Appendix II) which do not represent map subdomains. The modal planes intersect southwest in the

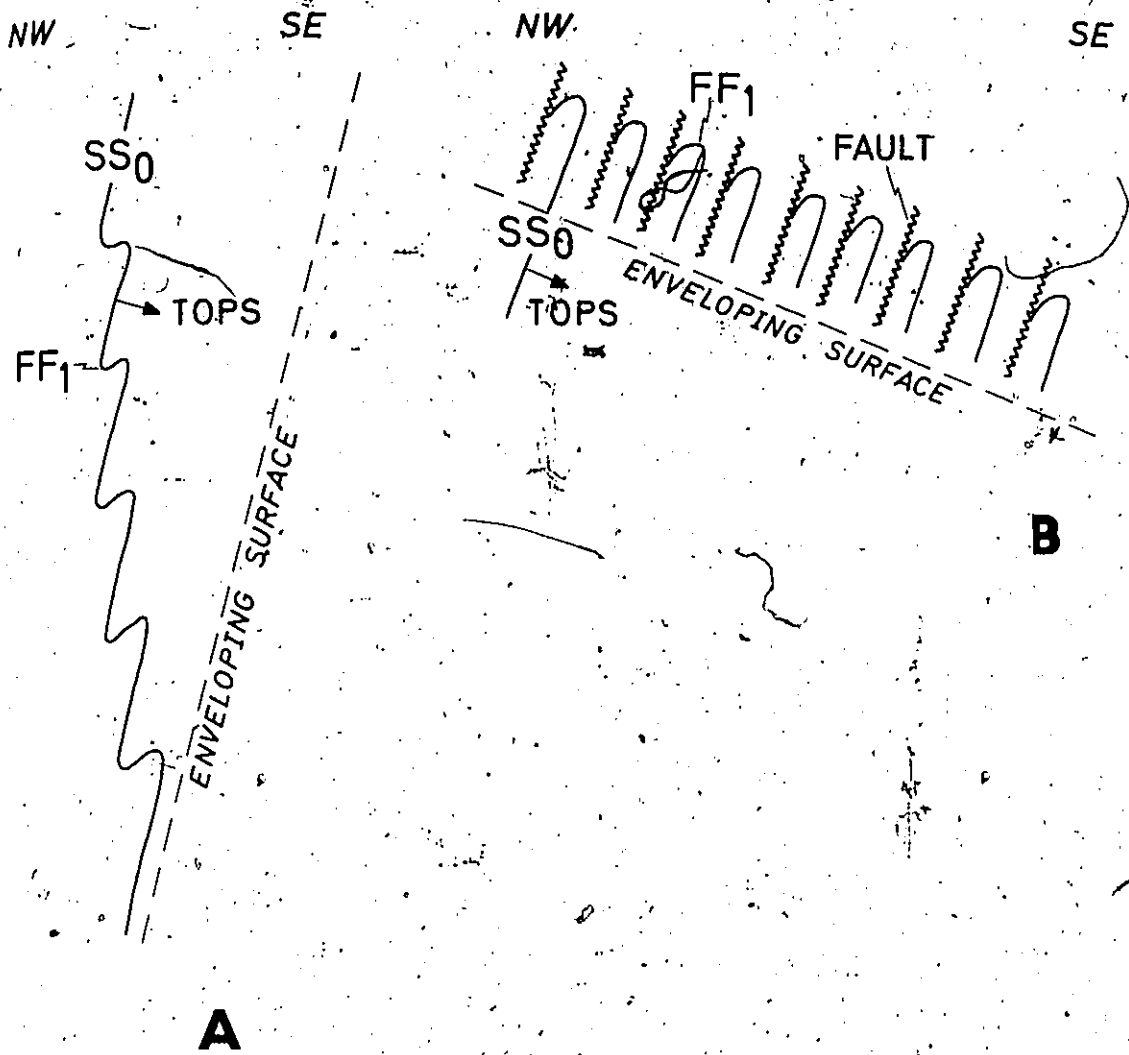


Fig. 19 Interpretations of  $FF_1$  folds and enveloping surface in the Connecticut Valley - Gaspé synclinorium. A) Asymmetric  $FF_1$  folds with long limbs overturned southeast form major structure with bed dominantly facing southeast and steep enveloping surface. B) Offsets along steep bedding-plane faults result in enveloping surface that dips gently southeast.

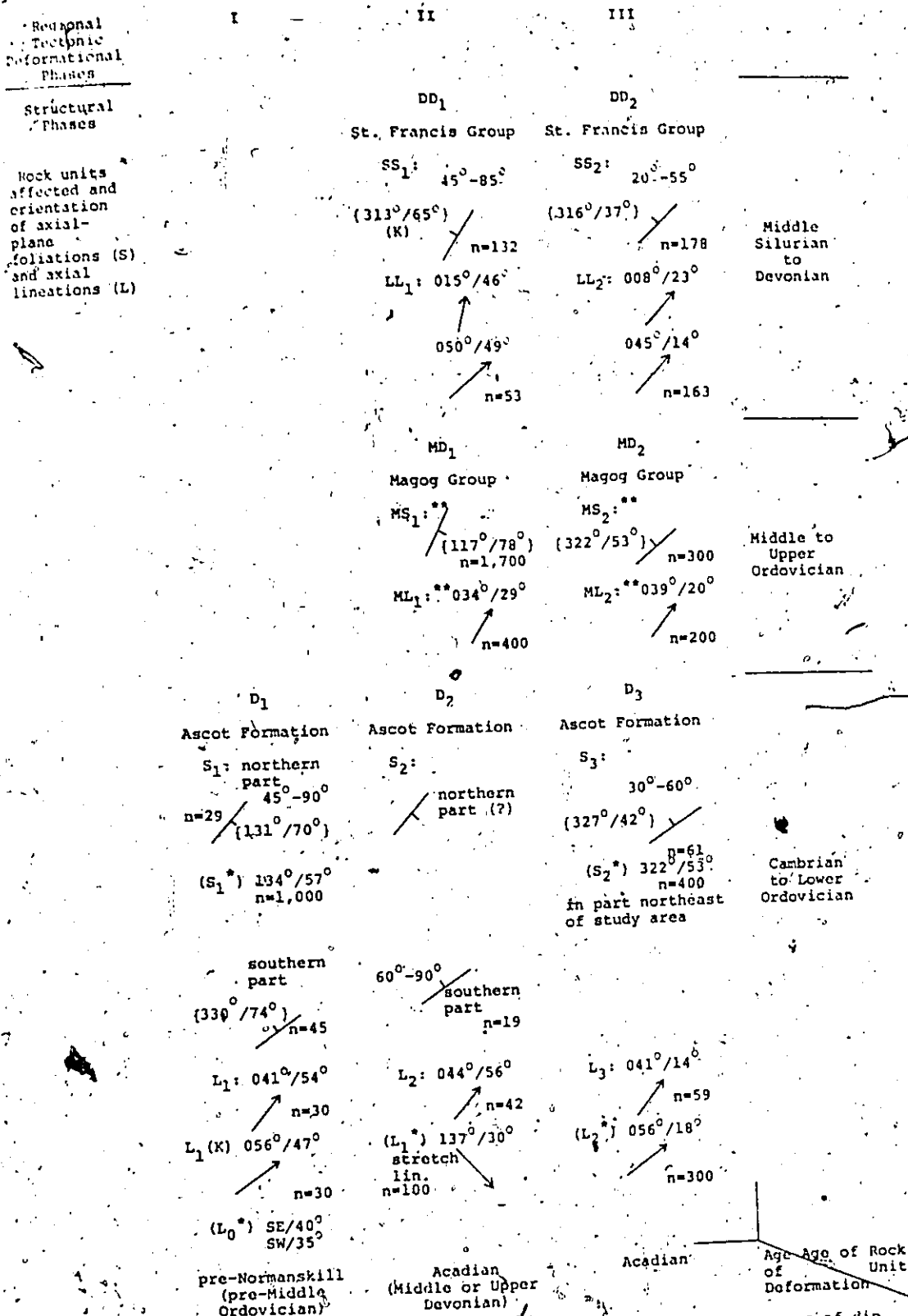
opposite direction to the modal plunges of  $LL_2$  so that the variations in dip of  $SS_1$  do not appear to be directly related to  $FF_2$  folds.  $SS_2$  is unimodal and intersects the two modal  $SS_1$  planes to form the observed bimodal  $LL_2$  lineations (Fig. 25b, Appendix II). The arrangement is as if after  $FF_1$  folding, but before  $FF_2$  and the development of  $SS_2$ ,  $SS_1$  (and parallel bedding) was folded on a scale larger than that of single outcrops. The fold scale is smaller than that of the major folds suggested by the  $S_1$  domains in the Ascot Formation, but the temporal relations to earlier and later small scale structures appears similar.

#### Correlation of Structures and Age of the Deformation

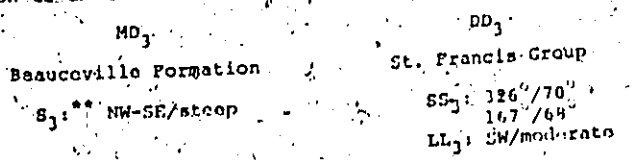
The method of correlating, and assigning ages to the structures is first to consider structures of the last phase of deformation and then to work back to structures of the first phase. The correlation into tectonic deformational phases I to III, which produced widespread structures is summarized in Table 9.

All structures in the Siluro-Devonian St. Francis Group are obviously no older than the Devonian (Acadian) orogenic event. Middle or Upper Devonian granites truncate all, except perhaps  $DD_3$  structures, thus  $DD_1$  and  $DD_2$  structures are definitely Devonian Acadian features. Locally developed  $DD_3$  structures, which were mainly observed near a granite pluton of presumed Mid-Devonian age (Lamarche, 1972a) are also considered to be Acadian.

Table 9 Correlation of Minor Structures and Age of Deformation



The orientations are ranges (~90% level) in dip of foliations, modal averages of dip lines ( ), and modal averages of lineations obtained from net projections (Appendix II), except those with asterisks (\*) from Lamarche (1965), and (\*\*) St-Julien (1963b)..  
 K = Kamb plot n = sample size  
 In addition to the above structures the following are locally present:



Tectonic Deformational Phase III

In the St. Francis Group mesoscopic folds,  $FF_2$ , and crenulation cleavage,  $SS_2$ , are comparable in form and orientation to the  $F_3$  folds and  $S_3$  cleavage in the Ascot Formation. As shown in Fig. 25 (Appendix II) and Table 9, the modal averages of  $S_3$  and  $SS_2$  are nearly coincident (less than  $10^\circ$  apart). The  $D_3$  and  $DD_2$  structures are thus considered to be coeval and both are assigned a Devonian (Acadian) age. This is in agreement with Baer (1961), Lamarche (1965), St-Julien (1963b) and Cady (1969).

In the Ascot Formation in the Sherbrooke area, the modal average of 400  $S_2$  cleavage planes ( $S_3$  in the present study) of Lamarche (1965) is  $322^\circ/53^\circ$  and the modal average of 300  $S_2$  cleavage planes ( $MS_2$  in the present study) from the Middle to Upper Ordovician Sherbrooke and Beauceville Formations in the St-Elie d'Orford area immediately to the west is also  $322^\circ/53^\circ$  (St-Julien, 1963b). It is very unlikely that two unrelated deformational phases would produce statistically identical orientations, therefore  $D_3$  and  $MD_2$  are also considered to be coeval and Acadian. This interpretation differs from that of Lamarche and St-Julien (1969) since they considered the deformation in the Magog Group to be Taconic.

It is not understood why the Siluro-Devonian Glenbrooke Group, which to the west overlies the Beauceville Formation, and also the Upper Ordovician (?) East Branch Pond Formation, (Fig. 4), does not display structures similar to  $MS_2$ . Possibly the deformation died out upward and westward, however further work is necessary in this area in order to determine the

structural relationships. The relationships between structures in the Glenbrooke Group and structures further west in the Sutton Mountains remains unresolved (see Rickard, 1965 p. 533). Rodgers (1971) is of the opinion that most of the deformation in the Sutton Mountains is due to the Taconic orogeny.

### Tectonic Deformational Phase II

Although in the study area few hinges of  $FF_1$  folds are exposed, it is apparent from the steep dips of  $SS_1$  that the folds, except on the flat limbs of  $FF_2$  structures, are mainly upright or steeply inclined northwest and southeast (see cross sections Figs. 6 and 9). There is little evidence of recumbent  $FF_1$  minor or major folds as suggested by Cady (1969 p. 37).

In the Disraeli area about 45 miles (72 km) northeast of Sherbrooke near the Weedon Mountain complex (a northerly continuation of the Stoke Mountain complex) (Fig. 3), St-Julien (1970a) noted that first generation tight folds (no others are described) have axial planes dipping steeply to the southeast (Clark p. 42, in Cooke, 1937). These folds are of form and orientation similar to the first generation folds described by St-Julien (1970a) in the rocks of the St. Victor synclinorium (Beauceville, St. Victor, Sherbrooke and Lake Aylmer Formations). Moreover, to the northeast, beyond the extent of the Weedon Mountain complex where the Beauceville Formation is in contact with the St. Francis Group, there are no apparent structural differences (Clark p. 33, in Cooke, 1937). Thus from the study area and outside where the rock

groups are in juxtaposition and later structures are less pronounced, the similarities in style suggest that the  $FF_1$  folds in the St. Francis Group formed at the same time as the  $MF_1$  folds in the Magog Group. If so, the  $MF_1$  folds are Acadian structures, not Taconic as indicated by Cady (1969, p. 109) and Lamarche, 1972a p. 5). Also the first folds in the Magog Group appear to be Acadian since they can be traced into the overlying Siluro-Devonian Lake Aylmer Formation (Fig. 4). This interpretation differs from that of St-Julien (1963b) who considers them to be pre-Normanskill (early Taconic).

The combined  $S_1:S_2$  foliation in the Ascot Formation, although striking in part oblique to the outcrop boundary, is parallel to  $SS_1$  in the adjacent parts of the St. Francis Group and to  $MS_1$  in the Magog Group. Thus because of the closely similar orientations  $F_2$  folds are considered to have developed at the same time as  $FF_1$  and  $MF_1$ , that is they are Acadian structures. This interpretation is consistent with a Devonian K-Ar date ( $322 \pm 14$  million years; Wanless, Stevens, Lachance and Edmonds, 1968) and a Rb-Sr date (384 million years; Wanless, 1969 (compiled from unpublished data) obtained from the albite granite north of Sherbrooke. The granite is foliated parallel to  $S_1:S_2$  and probably the age dates reflect the Acadian deformation. This interpretation differs from that of Lamarche (1973) who considered, without giving reasons, that the  $F_2$  folds were Taconic (Middle Ordovician).

Tectonic Deformational Phase I

85 D<sub>1</sub> deformation of the Ascot Formation produced a schistose foliation S<sub>1</sub> parallel to the bedding. Fragments of albite granite similar to that near Sherbrooke and randomly oriented schistose clasts are present at the base of the Upper Ordovician Sherbrooke Formation (Magog Group) to the west of the Stoke Mountain complex (Lamarche, 1962), as well as in the Siluro-Devonian St. Francis Group to the east (Lamarche, 1967). This evidence, in addition to the absence in the Beauceville Formation of fold structures analogous to F<sub>1</sub> folds, suggests that these structures are older than the Beauceville Formation. Furthermore, to the northeast Lower Ordovician (?) ophiolites rest unconformably over deformed rocks (Caldwell Group) (Lamarche, 1972b) that may be equivalent in age to the Ascot Formation. A Lower Middle or early Ordovician age of deformation is consistent with development in an early phase, the Stoke Mountain phase (Cady, 1969 p. 108), of the Taconic orogeny. The suggested age for F<sub>1</sub> folding is in agreement with St-Julien (1963b) and Lamarche (1965) but not that of Baer (1961).

IV

SYNTHESIS

Tectonic History

The rocks and structures investigated suggest the following sequence of events for the study area and vicinity. Fig. 20 is a pictorial summary of the tectonic history shown in 9 stages of development.

During the Cambrian and/or Lower Ordovician, basaltic and rhyolitic volcanic flows and sediments (flysch-like graywackes, mudstones and tuffs) were deposited in a eugeosynclinal environment (Fig. 20 stage 1) (see also Cady, 1967).

D<sub>1</sub> deformation (Tectonic deformational phase I) in the Ascot Formation was accompanied by the production of small scale isoclinal folds and regional metamorphism to produce sericite (muscovite) and chlorite aligned along the axial-plane foliation, S<sub>1</sub> (Fig. 20 stage 2). The folds may have been recumbent and associated with large nappe structures as suggested by Rickard (1965 p. 531) for the earliest folds of similar style in the Sutton Mountain complex to the west.

Lower Ordovician (or early Middle Ordovician) albite granitic and ultramafic rocks intruded the deformed rocks of the Ascot Formation (Stoke Mountains) (Fig. 20 stage 3) possibly at the same time as ophiolites (Lamarche, 1972b) northeast of the study area.

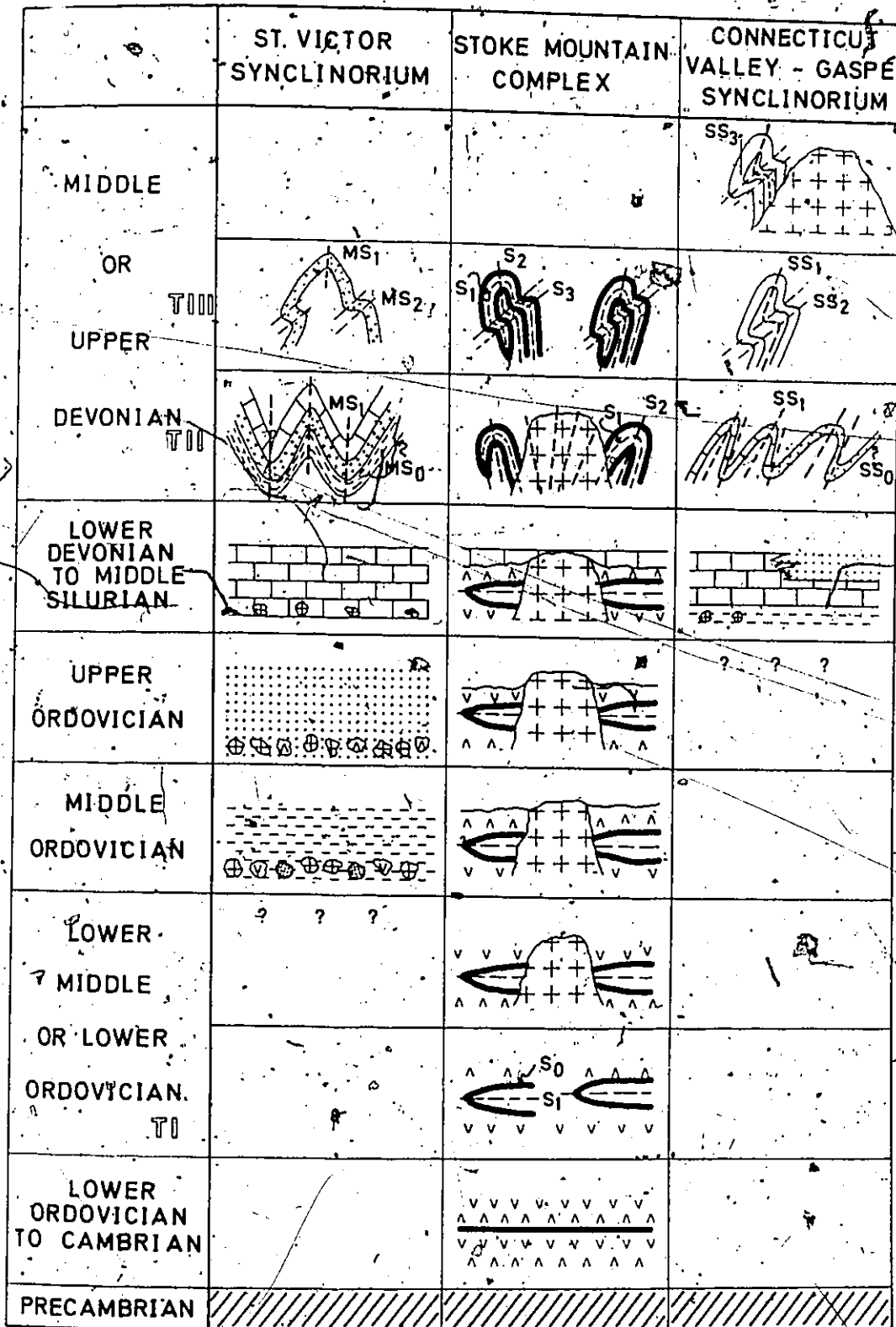


Fig. 20. Pictorial summary of the geological events in the Lake Massawippi area. The numbers 1 to 9 correspond to the Tectonic stages discussed in the text and the symbols TI to TIII correspond to the Tectonic deformational phases as in Table 9.

Following, and possibly during stages 2 and 3 deposition of a flysch type assemblage (Beauceville Formation) took place in the St. Victor synclinoorium to the northwest of the Stoke Mountain complex which was uplifted and eroded (Fig. 20 stage 4). To the northeast, in the Weedon area (Fig. 3), material was also derived from the Sutton Mountains (Duquette, 1961). The flysch sedimentary rocks may represent deposition following a westward moving allochthon as suggested by Zen (1972 p. 35) or rapid deposition in a graben structure between the Stoke and Sutton Mountain complexes.

The Upper Ordovician was a period of continued erosion of the Stoke Mountain complex. The sediments were deposited disconformably over the Beauceville Formation as conglomerates, sandstones and shales of the Sherbrooke and equivalent East Branch Pond Formations (Fig. 20 stage 5).

Due to regional uplift Lower Silurian deposits were not preserved and near the positive Stoke Mountain block the Sherbrooke and Beauceville Formations were eroded. During the Upper Silurian and Lower Devonian carbonates, shale and sandstone (Glenbrooke and St. Francis Groups, and Lake Aylmer Formation) were deposited in both the St. Victor and Connecticut Valley - Gaspé synclinooriums (Fig. 20 stage 6). Duquette (1961) indicates that in the Weedon area the sedimentary rocks overlapped the Stoke Mountain complex.

In the Middle or Upper Devonian period rocks throughout the study region were folded (Tectonic deformational phase II) during the Acadian orogeny (Fig. 20 stage 7). In apparent contrast to the Taconic structures the resultant tight folds are upright or steeply inclined suggesting a large component of horizontal shortening. In the St. Francis Group, bedding-

plane faults may have developed as the folds tightened, resulting in stratal repetitions and a low regional dip east though most beds are steep and face east.

Continued Acadian deformation (Tectonic deformational phase III) again folded all the rock units (except the Devonian granites) within the study area (Fig. 20 stage 8). The orientation of the folds, with most axial planes dipping  $30^{\circ}$ - $50^{\circ}$  northwest across the steeper earlier foliations might suggest regional compression in a direction inclined southeast. However, in gross geometry the folds larger than crenulations are in discontinuous pairs; the rock at this scale is not folded throughout. Hence as with kink bands, which are also discontinuous fold pairs (Fig. 21) the axial planes may be oblique to the direction of bulk shortening. Unlike kink bands that tend to be at high angles ( $60^{\circ}$ +) to the external foliation (Weiss, 1969) the axial planes are usually less than  $50^{\circ}$  to the long apparently unrotated limbs. Hence the folds are only partly analogous to kinks and the directions of bulk strain is uncertain.

Middle or Upper Devonian granitic plutons intruded the deformed rocks of the St. Francis Group, resulting in a local steep crenulation cleavage (Fig. 20 stage 9).

## Tectonic Evolution in Relation to Plate Tectonics

### Introduction

Plate tectonic models have recently been used to explain the development of the Appalachian orogen, particularly the northern part (Dewey and Bird, 1970; Bird and Dewey, 1970; Zen, 1972;

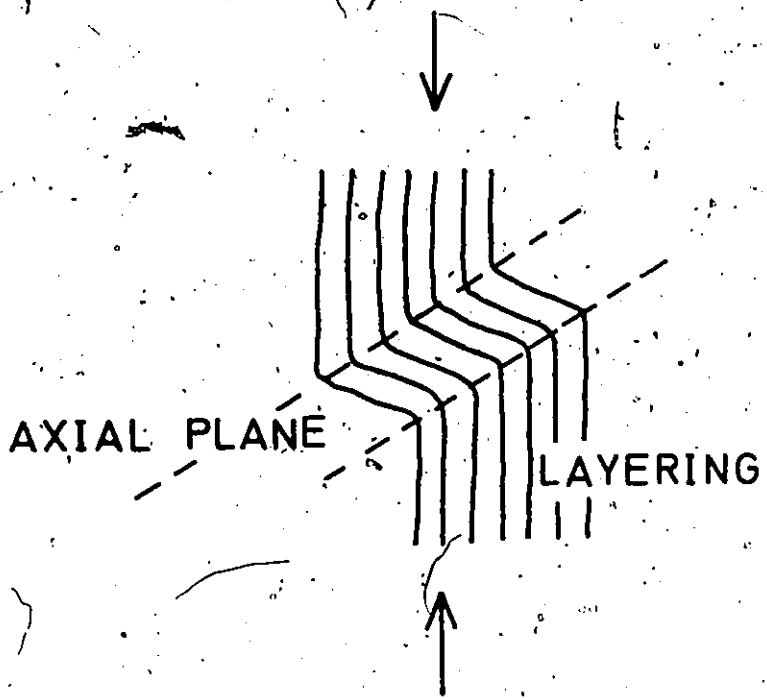


Fig. 21 Experimentally formed kink band with axial plane oblique to the direction of external shortening (Weiss, 1969).

Williams, Kennedy and Neale, 1972; Rickard and Fisher, 1973; Williams and Smyth, 1973 and Laurent, 1973). Briefly the Dewey and Bird (1970) and Bird and Dewey (1970) model is as follows:

Opening of a proto-Atlantic ocean during late Precambrian to early Ordovician times was accompanied by down faulting of the continental margin. Infilling with sediments and volcanics formed shelf (miogeoclinal) and continental rise (eugeosynclinal) successions. Later in the early Ordovician there was contraction of the Atlantic region. An oceanic trench developed near the newly formed continental margins and the oceanic lithosphere was subducted (underthrust) down a Benioff zone dipping west under the continent. Oceanic volcanics were erupted above the descending plate and an island arc was formed. Rising gabbroic and granodioritic magmas formed a thermal dome or orogenic welt from which there was sediment transport, flysch deposition, and gravity sliding, both towards the ocean and continent. Further rise and lateral expansion of the magmatic mobile core to the orogenic welt led to overthrusting towards the continent (and ocean?). The resultant Taconic orogenic belt is considered to be of the Cordilleran type.

Continued subduction of the oceanic lithosphere eventually resulted in closure of the proto-Atlantic, continental collision, and Devonian Acadian deformation over a wide area. Towards the end of orogenesis, granites were intruded from the mobile core.

Current opinion is divided as to whether or not the data from the Northern Appalachians supports such a model (Zeitz and Zen, 1973). It is thus relevant to determine if the model

can readily explain the rock facies, structures and deduced evolution of the study region.

### Facies Relations

The origin of some of the rock groups can readily be equated with the model. The Lower Ordovician or older acid volcanics of the Ascot Formation could have formed at the distending margin of the continent. On the other hand, Lamarche (1973) is of the opinion that the volcanics are island-arc deposits.

The Middle Ordovician black slates and graywackes of the Magog Group are flysch deposits that, like the correlative Normanskill of Vermont, could have accumulated in an exogeosyncline marginal to a rising thermal dome to the east.

Not so clear is the provenance of the Siluro-Devonian carbonates, slates and sandstones of the Glenbrooke and St-Francis Groups and Lake Aylmer Formation (Gaspé Limestone Group of Logan, 1863). In particular, why the stable low energy depositional conditions indicated by the carbonates and slates should prevail if subduction and tectonic mobility continued. An analogy could be made with the Upper Ordovician and Silurian limestones and shales of the Aroostook and Matapedia Groups in northern Maine, New Brunswick and southern Gaspé. These are interpreted (Bird and Dewey, 1970 p. 1049) to have been deposited in a static small-ocean basin between two volcanic arcs. Plate consumption under the northwestern arc, (Oliverian) eventually contracted the basin and presumably led to Acadian deformation. However, in the study region

similar spatial relations are not obvious for the period of Siluro-Devonian sedimentation. For example there is no evidence that the limestones were deposited east of a subduction zone and island arc. Another possibility is that the model should be modified and that the limestones indicate a Siluro-Devonian pause in the process of subduction.

### Structural Succession

Following the plate-tectonic model, deformational phase I  $F_1$  recumbent folds in the Stoke Mountain complex are Taconic features that could have formed by gravity sliding from an orogenic welt. Unfortunately the possible position or direction of the welt is not clear, as  $F_1$  folds are not exposed sufficiently to determine vergence patterns and possible directions of sliding. South of the area, stratigraphic relations have established that the Taconic Klippen moved from the east (Zen, 1972), but vergence of small scale recumbent folds like  $F_1$  is not obvious and it is not necessary that the folding was directly related to westward gravity sliding or overthrusting. The deformational phase II steeply inclined or upright tight folds that imply horizontal compression could have resulted from the continent-continent collision in Mid-Devonian times. The deformational phase III folds that suggest restricted subvertical shortening are not so obviously directly fitted into the plate tectonics model.

In summary, the rock facies and structural evolution can be explained in terms of plate tectonics, but some modifications of the model, such as interruptions in the process of

subduction, may be necessary.

#### Problems and Suggestions for Future Work

- 1) The evidence from the small scale structures described does not clarify whether or not thrust faults are present, such as along the boundaries of the Stoke Mountain complex (Kerr, 1923). The nature of the large scale folds suggested by the reversals in dip direction of bedding in the St. Francis Group are also not clear. Possibly detailed lithological mapping and further determinations of stratigraphic tops could result in a more detailed outcrop pattern and reveal major folds, stratal repetitions, and disjunctions at thrust boundaries.
- 2) Correlation of structures in the St. Francis Group with those in the Magog Group is not readily made across the intervening Stoke Mountain complex. A detailed structural study to the northeast beyond the complex where the groups are in juxtaposition is required to test the proposed time relations.
- 3) Within the Stoke Mountain complex, the time of development of the foliation affecting the albite granite is not well defined. The foliation should be re-examined and compared with that in the adjacent rock of the Ascot Formation.
- 4) Orientations of folds have suggested a temporal variation during Acadian deformation in the direction of maximum bulk shortening from near horizontal to near vertical. How the direction of extension might have varied both in space and time is not known. Measurements of grains, pebbles and

agglomerate fragments elongated within foliation planes ( $S_2$ ;  $SS_1$  and  $MS_1$ , see St-Julien and Lamarche, 1965) may indicate spatial variations, at least during the early phase of Acadian deformation. Such deformation may reveal whether or not the steep plunge of many  $F_2$  folds and axial lineations is the result of rotation towards a steep direction of extension.

5) The reason why the majority of the minor folds in each generation of both the Taconic and Acadian deformational periods consistently plunge northeast is not clear. No obvious major structure plunges in this direction. Further work to the north in the Stoke Mountain belt and adjoining rocks should clarify whether the plunges are similar throughout the region.

6) The use of similarities in orientation of structures as evidence for time equivalence is open to question, particularly in comparing the  $F_2$  folds in the Stoke Mountain complex with Acadian first folds. That the evidence may be interpreted differently is demonstrated in northern and western Gaspé Peninsula where steeply inclined second phase folds in Cambro-Ordovician rocks are shown to be Taconic structures, although they trend parallel to Acadian folds in adjacent Siluro-Devonian rocks (Carrara and Fyson, 1973).

Detailed investigations between the study area and Gaspé along the interface between the Siluro-Devonian and Cambro-Ordovician rocks might resolve the apparent contradictions in interpretation. It might also be possible to obtain additional radiometric dates on cross-cutting plutons.

## REFERENCES

- Albee, A. L., 1968, Metamorphic zones in northern Vermont: in Zen, E-an, White, W. S., Hadley, J. B., and Thompson Jr., J. B., editors; Studies of Appalachian geology, northern and maritime: p. 329-341.
- Ami, H. M., 1960, Synopsis of the geology of Canada: Royal Society of Canada Transactions, 2<sup>nd</sup> ser., v. 6, sec. IV.
- Ambrose, J. W., 1943, Preliminary map of Stanstead; Stanstead and Bromé counties, Quebec: Canada Geol. Surv., Paper 43-12.
- Baer, A. J., 1961, Structural analysis of Appalachian structures in the Memphremagog area: Seminars in Tectonics, McGill University, mss. 20-22.
- Bancroft, J. A., 1915, The copper deposits of the Eastern Townships of the Province of Quebec: Quebec Dept. Colonization, Mines and Fisheries, Mines Branch.
- Béland, J., 1952, St. Maglorie area; Montmagny, Bellechasse and Dorchester counties, Quebec: Quebec Dept. Mines, Prelim. Rept., 279, 11p.
- \_\_\_\_\_, 1967, Contributions from systematic studies of minor structures in the southern Quebec Appalachians: Roy. Soc. Canada Spec. Pub. 10, p. 48-56.
- Berry, W., 1962, On the Magog, Quebec graptolites: Amer. Jour. Sci., v. 260, p. 142-148.
- Bird, J. M., and Dewey, J. F., 1970, Lithosphere plate-continental margin tectonics and the evolution of the Appalachian orogen: Geol. Soc. America Bull., v. 81, p. 1031-1060.

Boucôt, A. J., and Drapeau, G., 1968, Siluro-Devonian rocks

of Lake Memphremagog and their correlatives in the Eastern

Townships: Quebec Dept. Nat. Res. Spec. Paper 1, 44p.

Burton, F. R., 1931, Commercial granites of Quebec; Part I -

south of the St. Lawrence River: Que. Bur. Mines, Ann.

Rept. part E.

Cady, W. M., 1960, Stratigraphic and geotectonic relationships

in northern Vermont and southern Quebec: Geol. Soc. Amer.

Bull., v. 71, p. 531-576.

\_\_\_\_\_, 1967, Geosynclinal setting of the Appalachian

Mountains in southeastern Quebec and northwestern New

England: Roy. Soc. Canada, Spec. Pub. 10, p. 57-68.

\_\_\_\_\_, 1969, Regional tectonic synthesis of northwestern

New England and adjacent Quebec: Geol. Soc. America Memoir

120; 181p.

Carrara, A., 1972, Structural geology of Lower Paleozoic

rocks, Mt. Albert area, Gaspé Peninsula, Quebec:

unpublished Ph.D. thesis, University of Ottawa, Ottawa,

Ontario.

\_\_\_\_\_, and Fyson, W. K., 1973, Taconic and Acadian folds

in northern and western Gaspé Peninsula, Quebec: Canadian

Jour. of Earth Sciences, v. 10, no. 4, p. 498-509.

Carrière, E. G., 1954, The geology of the Suffield Mine:

unpublished M.Sc. thesis, McGill University, Montreal,

Quebec.

Clark, T. H., 1934, Structures and stratigraphy of southern

Quebec: Geol. Soc. America Bull., v. 45, no. 2, p. 1-20.

\_\_\_\_\_, 1937, Beauceville, St. Francis and Lake Aylmer

series, in Cooke, H. C., 1937; Thetford, Disraelie and Eastern half of Warwick map-areas, Quebec: Geol. Surv. Canada, Mem. 211, p. 33-50.

Cooke, H. C., 1932, Asbestos deposits of Thetford area, Quebec: Canada Geol. Surv., Summary Rept., 1931, Part D, p. 1-24.

\_\_\_\_\_, 1933, Thetford district, Quebec: Canada Geol. Surv., Summary Rept., 1932, Part D, p. 44-55.

\_\_\_\_\_, 1937, Thetford, Disraeli and Eastern half of Warwick map-areas, Quebec: Geol. Surv. Canada, Mem. 211, 160p.

\_\_\_\_\_, 1948a, Sherbrooke, Quebec: Geol. Surv. Canada, map 911A.

\_\_\_\_\_, 1948b, Dudswell, Quebec: Geol. Surv. Canada, map 908A.

\_\_\_\_\_, 1948c, Scôtstown, Quebec: Geol. Surv. Canada, map 913A.

\_\_\_\_\_, 1950, Geology of a southwestern part of the Eastern Townships of Quebec: Geol. Surv. Canada, Memoir 257, 142p.

\_\_\_\_\_, 1957, Coaticook - Malvina area: Quebec Dept. Mines, Geol. Rept., 69, 37p.

Currie, L. W., and Jahns, R. H., 1941, Ordovician stratigraphy of central Vermont: Geol. Soc. America Bull., v. 52, p. 1487+1512.

de Römer, H., 1961, Structural elements in southern Quebec, northwestern Appalachians, Canada: Geol. Rundschau, v. 51, p. 267-280.

Dewey, J. F., and Bird, J. (M.), 1970, Mountain belts and the new global tectonics: Jour. of Geophysical Research, v. 75, p. 2625-2647.

Divi, R. R., and Fyson, W. K., 1973, Folds and strain in Grenville metamorphic rocks, Bancroft, Ontario: Geol. Soc. America Bull., v. 84, no. 5, p. 1607-1618.

Doll, C. G., 1951, Geology of Memphremagog quadrangle and the southeastern portion of the Irasburg quadrangle Vermont: Vermont Development Commission, Montpelier, Vermont, Bull. no. 3, 113p.

\_\_\_\_\_, 1961, Centennial geological map of Vermont: Vermont Geol. Surv., Montpelier.

Donath, F. A., and Parker, R. B., 1964, Folds and folding: Geol. Soc. America Bull., v. 75, p. 45-62.

Douglas, G. V., 1941, Eustis Mine area, Ascot Township: Quebec Dept. Mines and Maritime Fisheries, Geol. Rept., no. 8, 31p.

Drapeau, G., 1961, Geology of the Lake Memphremagog syncline: M.Sc. thesis, Massachusetts Institute of Technology.

Duquette, G., 1961, Geology of the Weedon Lake area and its vicinity, Wolf and Compton counties, Quebec: D.Sc. thesis, Laval University.

Ells, R. W., 1887, Report on the geology of a portion of the Eastern Townships of Quebec, relating more especially to the counties of Compton, Stanstead, Beauce, Richmond and Wolfe: Canada Geol. Surv., 2<sup>nd</sup> Ann. Rept., 1886, v. III, Part J, 70p. and map 251.

\_\_\_\_\_, 1889, Second report on the geology of a portion

of the Province of Quebec: Canada Geol. Surv., Ann. Rept. 1887-1888, v. III, Part II, Part K.

\_\_\_\_\_, 1896, Report on a portion of the Province of Quebec comprised in the southwest sheet of the "Eastern Townships" map (Montreal Sheet): Canada Geol. Surv., 7<sup>th</sup> Ann. Rept., 1894, Part J and map 571.

Faessler, C., 1939, Risborough - Marlow area; Frontenac county: Québec Dept. Mines, Geol. Rept. no. 3, 18p.

Gorman, W. A., 1954, Ste. Justine area; Montmagny, Bellchase and Dorchester counties: Quebec Dept. Mines, Preliminary Report 314.

G. S. C., 1954a, Sherbrooke; Sherbrooke, Compton, Richmond and Stanstead counties, Quebec; Aeromagnetic map 182G: G. S. C. Dept. of Mines and Technical Surveys, Geophysics Section.

\_\_\_\_\_, 1954b, Orford; Shefford, Sherbrooke, Brome, Stanstead and Richmond counties, Quebec; Aeromagnetic map 173G: G. S. C. Dept. of Mines and Technical Surveys, Geophysics Section.

\_\_\_\_\_, 1954c, Coaticook; Stanstead, Compton and Sherbrooke counties, Quebec; Aeromagnetic map 175G: G. S. C. Dept. of Mines and Technical Surveys, Geophysics Section.

\_\_\_\_\_, 1954d, Memphremagog; Stanstead and Brome counties, Quebec; Aeromagnetic map 182G: G. S. C. Dept. of Mines and Technical Surveys, Geophysics Section.

Harvie, R., 1917, Thetford - Black Lake mining district, Quebec: Geol. Surv. Canada, Summary Rept., 1916, p. 228-229.

Kamb, W. B., 1959, Ice petrofabric observations from Blue Glacier, Washington, in relation to theory and experiment: Jour. Geophysics Res., v. 64, p. 1891-1909.

Kelly, R., 1963, ~~Ste-Cécile~~ St-Sébastien area, Frontenac county: mss., Quebec Dépt. Nat. Rés.

Kerr, F. A., 1923, Manuscript on the geology of the Memphremagog quadrangle: unpublished, on file at the Geol. Surv. Canada library, Ottawa.

Knox, J. K., 1917, Southwestern part of Thetford and Black Lake mining district (Coleraine Sheet). Geol. Surv. Canada, Summary Rept., 1916, p. 229-245.

Lamarche, R. Y., 1962, Etudes des conglomérats de la région Orford - Sherbrooke: M.Sc. thèse, Université Laval, Quebec.

\_\_\_\_\_, 1965, Géologie de la région de Sherbrooke, Comté de Sherbrooke, Quebec: D.Sc. thèse, Université Laval, Quebec.

\_\_\_\_\_, 1967, Geology of Beauvoir - Ascot Corner area; Sherbrooke, Richmond and Compton counties, Quebec: Quebec Dept. Nat. Res., Min. Dep. Serv. Prelim. Rept. 560, 16p.

\_\_\_\_\_, 1970, Effects of refolding on the location and shape of stratabound sulphide deposits in the Ascot metavolcanics of the Eastern Townships, Quebec: Geol. Assoc. Canada and Mineral Assoc. Canada, Program and Abstracts, Ann. Meeting, Winnipeg, Manitoba, p. 32-33.

\_\_\_\_\_, 1972a, Structural geology of Sherbrooke area: 24<sup>th</sup> International Geol. Congress, Excursion B-05, guidebook 17p.

\_\_\_\_\_, 1972b, Ophiolites of southern Quebec: Publ.

Earth Physics Branch, Dept. of E. M. R., Ottawa, vol. 42,  
no. 3, p. 65-69.

\_\_\_\_\_, 1973, Volcanogenic sulphide deposits of the  
Eastern Townships of southern Quebec: Paper presented at  
the conference on "Metavolcanic massive sulphide deposits,  
with reference to the northern Appalachians," McGill  
University, Montreal, Nov. 30, 1973.

\_\_\_\_\_, and St-Julien, P., 1969, Structural geology  
of the Sherbrooke area; in guidebooke for excursions nos.  
4, 5, 7 and 8A: Geol. Assoc. Canada and Mineral Assoc.  
Canada, Montreal, p. 87-93.

Laurent, R., 1973, The Thetford Mines ophiolite, Paleozoic  
"flake" of oceanic lithosphere in the northern Appalachians  
of Quebec: Geol. Soc. of America, abstracts, northern  
section, v. 5, no. 2, p. 188.

Logan, Sir W. E., 1849, On the geology of the country on the  
south side of the St. Lawrence from Montreal and Lake  
Champlain to the Chaudière River, Quebec: Canada Geol.  
Surv., Progress Rept., 1847-1848, 165p.

\_\_\_\_\_, 1863, Geology of Canada: Canada Geol. Surv.,  
Progress Rept. to 1863, 933p.

Lyons, J. B., and Faul, H., 1968, Isotope geochronology of the  
northern Appalachians: in Zen, E-an, White, W. S., Hadley,  
J. B., and Thompson Jr., J. B., editors; Studies of  
Appalachian geology, northern and maritime: p. 305-318.

Mackay, B. R., 1921, Beauceville map-area, Quebec: Canada  
Geol. Surv., Memoir 127, 105p.

Marleau, R. A., 1958, East Megantic and Armstrong areas,

Electorial districts of Frontenac and Beauce, Quebec:

Quebec Dept. Mines, Prelim. Rept. 362, 7p.

\_\_\_\_\_, 1968, Woburn - East Megantic - Armstrong area;

Frontenac and Beauce counties, Quebec: Quebec Dept. Nat.

Reš. Geol. Rept. 131, 55p.

McGernigle, H. W., 1935, Mount Megantic area, southeastern

Quebec, and its placer gold deposits: Ann. Rept. of the

Quebec Bureau of Mines, 1934 part D, p. 63-104 and map 312.

McDonald, B. C., 1966, Auriferous till in the Eastern

Townships, southeastern Quebec: Geol. Surv. Canada,

Paper 66-2, p. 51-54.

\_\_\_\_\_, 1967, Surficial geology, Sherbrooke - Orford -

Memphremagog, Quebec: Geol. Surv. Canada, map 5-1966.

\_\_\_\_\_, 1969, Surficial geology of La Patrie -

Sherbrooke area, Quebec, including Eaton River watershed:

Geol. Surv. Canada, Paper 67-52, 21p.

Osberg, P. H., 1965, Structural geology of the Knowlton -

Richmond area, Quebec: Geol. Soc. America Bull. v. 76,

p. 223-250.

Pavrides, L., Menscher, E., Naylor, R. S., and Boucot, A. J.,

1964, Outline of the stratigraphic and tectonic features

of northeastern Maine: U. S. Geol. Surv., Prof. Paper

501-C, p. 28-38.

Page, L. R., 1968, Devonian plutonic rocks in New England: in

Zen, E-an, White, W. S., Hadley, J. B., and Thompson Jr.,

J. B., editors; Studies of Appalachian geology, northern

and maritime: p. 371-383.

Perkins, E. H., 1925, The Moose River synclinorium and its

- associated Formations: American Jour. Sci., 5<sup>th</sup> ser.,  
v. 10, p. 368-375.
- Ramsay, J. G., 1967, Folding and fracturing of rocks: McGraw-  
Hill Book Company, 568p.
- Rickard, L., and Fisher, D., 1973, Middle Ordovician  
Normanskill Formation, eastern New York, age, stratigraphic  
and structural position: American Jour. of Science,  
v. 273, p. 580-590.
- Rickard, M. J., 1965, Taconic orogeny in the western  
Appalachians: experimental application of microtextural  
studies to isotopic dating: Geol. Soc. America Bull.,  
v. 76, p. 523-536.
- Rodgers, J., 1971, The Taconic orogeny: Geol. Soc. America  
Bull., v. 82, p. 1141-1178.
- Sauvé, P., Cloutier, J. P., and Genois, G., 1972, Base metal  
deposits of southeastern Quebec: 24<sup>th</sup> International Geol.  
Congress, Excursion B-07, guidebook.
- Selwyn, A. R. C., 1879, Observations on the stratigraphy of  
the Quebec Group: Geol. Surv. Canada, Rept. of Progress,  
1877-1878, part A.
- \_\_\_\_\_, 1883, Notes on the geology of southeastern  
portion of the province of Quebec: Canada Geol. Surv.  
Prog. Rept., 1880-1882, part A.
- Spry, A., 1969, Metamorphic textures: Pergamon Press Ltd., 350p.
- Stevenson, J. S., 1937, Mineralization and metamorphism at the  
Eustis Mine, Quebec: Ec. Geol., 32, p. 335-363.
- St-Julien, P., 1963a, Saint - Elie - d'Orford area; Sherbrooke  
and Richmond counties: Québec Dept. Nat. Res., Prelim.

Rept. 492, 14p.

\_\_\_\_\_, 1963b, Géologie de la région d'Orford -  
Sherbrooke, Quebec: D.Sc. thèse, Université de Laval.

\_\_\_\_\_, 1967, Tectonics of the Appalachian region of  
southeastern Quebec (southwest of the Chaudière River):

Roy. Soc. Canada Spec. Pub. 10, p. 41-47.

\_\_\_\_\_, 1970a, Geology of Disraeli area (eastern half);  
Frontenac, Wolfe and Megantic counties: Quebec Dept. Nat.

Res. Prelim. Rept. 587.

\_\_\_\_\_, 1970b, Orford - Sherbrooke area: Quebec Dept.

Nat. Res., map 1619.

\_\_\_\_\_, and Lamarche, R. Y., 1965, Geology of Sherbrooke  
area; Sherbrooke county, Quebec: Quebec Dept. Nat. Res.,

Prelim. Rept. 530, 34p.

Thompson Jr., J. B., and Norton, S. A., 1968, Paleozoic  
regional metamorphism in New England and adjacent areas:

in Zen, E-an, White, W. S., Hadley, J. B., and Thompson  
Jr., J. B., editors; Studies of Appalachian geology,  
northern and maritime: p. 319-327.

Wahless, R. K., Stevens, R. D., Lachance, G. R., and Edmonds,

C. M., 1968, Age determinations and geological studies,  
K-Ar isotopic ages: Geol. Surv. Canada, Rept. 8, Paper  
67-2, part A, p. 114-115.

\_\_\_\_\_, 1969, Isotopic age map of Canada: Geol. Surv.  
Canada, map 1256A.

Weston, T. C., 1899, Reminiscences among the rocks in  
connection with the geological survey of Canada: Warwick  
Brothers and Rutter, Toronto, 328p.

Weiss, L. E., 1969, Flexural slip folding of foliated model materials: in Baer, A. J., and Norris, D. K., editors; Proceedings, conference on research in tectonics. (kink bands and brittle deformation): Geological Survey of Canada, GSC Paper 68-52, p. 294-359.

Williams, H., Kennedy, M. J., and Neale, E. R. W., 1972, The Appalachian structural province: in Price, R. A., and Douglas, R. J. W., editors; Variations in tectonic styles in Canada: Geol. Assoc. Canada, Special Paper no. 11, p. 253-256.

\_\_\_\_\_ , and Smyth, W. R., 1973, Metamorphic aureoles beneath ophiolite suites and alpine peridotites: Tectonic implications with west Newfoundland examples: American Jour. of Science, v. 273, no. 7, p. 594-621.

Zen, E-an, 1972, The Taconide zone and the Taconic orogeny in the western part of the northern Appalachian orogen: Geol. Soc. America, Special Paper 135, 72p.

Zietz, I., and Zen, E-an, 1973, Northern Appalachians:

Geotimes, v. 18, no. 2, February, p. 24-28.

APPENDIX I

FOLD CLASSIFICATION

Some of the folded layers that were observed in the field have been classified, from photographs and hand specimens, according to the method of Ramsay (1967, p. 365 Fig. 7-24) (see Fig. 22).

The various folded layers, the locality in which they were observed, the lithology and the class of the folds are indicated for the Ascot Formation in Table 10 and for the St. Francis Group in Table 11.

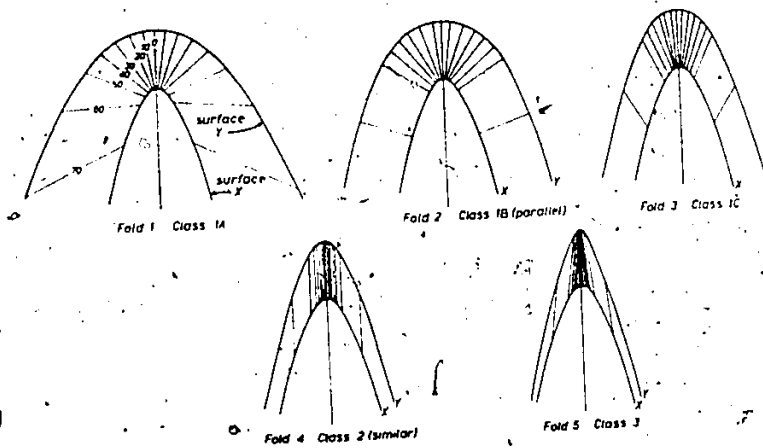


Fig. 22 Fundamental types of fold classes. Dip isogons have been drawn at  $10^\circ$  intervals from the lower to the upper surfaces X and Y. (after Ramsay, 1967, p. 365 Fig. 7-24)

Table 10 Fold Classification: Ascot Formation

Locality (one fold per locality)	Number of folded layers	Lithology	Class (according to Ramsay, 1967)
--	-------------------------------	-----------	---

F<sub>1</sub>

2	1	quartz vein	1C
5	1	sandstone	1C
5	1	sandstone	1C
321	7	siltstone	1C
335	1	siltstone	1C

F<sub>2</sub>

3	4	quartz vein	2
9	4	siliceous phyllite	1B
66	4	quartz vein	1C
69	4	quartz vein	1C
	1	quartz vein	1B
71	1	quartz vein	1B
	1	siltstone	1B
71	2	quartz vein	1C
88	1	quartz vein	1B
181	3	quartz vein	1C
194	3	quartz vein	1B

F<sub>3</sub>

2	2	quartz rich pelite	1C
5	1	quartz rich pelite	1C
66	8	quartz rich pelite	1C
66	1	quartz rich pelite	1B
	2	quartz rich pelite	1C
138	5	quartz rich pelite	1C
179	1	siltstone	3
	1	quartz rich pelite	1C
192	2	siltstone	3

Table 11 Fold Classification: St. Francis Group

Locality (one fold per locality)	Number of folded layers	Lithology	Class (according to Ramsay, 1967)
--	-------------------------------	-----------	---

FF<sub>1</sub>

25	1	calcareous micaceous siltstone	2
53	1	limestone	1C
185	5	calcareous siltstone and slate	1C
263	14	limestone	1C
	14	calcareous micaceous siltstone	2

FF<sub>2</sub>

23	1	limestone	1C
33	4	limestone	1B
34	3	limestone	1B
36	2	siliceous limestone	3
40	5	siliceous limestone	3
45	8	limestone	1B
170	1	calcareous siltstone	1C
185	2	siltstone	1C
244	3	silty limestone	1C
248	7	siltstone	3
	3	limestone	1B
259	3	limestone	1C
	5	limestone	1C

APPENDIX II

EQUAL AREA NET PROJECTIONS

The equal area net projections were plotted employing a program by Dr. K. J. Rosengren of the Department of Geophysics and Geochemistry, Australian National University, slightly modified by Carrara (1972).

The following three different types of diagrams are plotted for each set of data:

- 1) Scatter diagram
- 2) Schmidt method contour diagram
- 3) Kamb method contour diagram

The Schmidt method and scatter diagrams are often used so no additional explanation is necessary. However, since without the use of a computer the Kamb method is time consuming, and less frequently used, it is not as well known.

The purpose of the Kamb method contour diagram is to determine whether or not, on a statistical basis, the orientation densities are significant. Kamb (1959, p. 1908) states that: "The measure of statistical significance is the probability that the observed orientation density could have resulted from random sampling of a population that lacks preferred orientation. To control this probability, the area  $A$  of the counter used in the conventional (Schmidt ( $A=0.01$ )) contouring procedure is so chosen that, if the population lacks preferred orientation, the number of points  $n$  that will actually

fall within the area under random sampling of the population. This insures that the observed orientation densities, if obtained by random sampling of a non-preferentially oriented population, will not fluctuate wildly from the expected density  $E/A$ . Observed densities that differ from  $E/A$  by more than two or three times the standard deviation  $\sigma$  (for random orientation) are then likely to be significant, and the more so if the significantly higher densities are clustered in one portion of the diagram. The observed densities are therefore contoured in intervals of  $2\sigma$ , at the values  $0$ ,  $2\sigma$ ,  $4\sigma$ , etc., the expected density  $E$  for no preferred orientation being  $3\sigma$ ."

Since for large numbers of data (over 200) the Kamb and Schmidt methods are similar, the Kamb method is of greater usefulness for small populations where the possibility of orientation densities that are statistically insignificant is great with the Schmidt contouring method. It is for such small populations that both the Kamb and Schmidt plots are included for comparison in the present study.

Since the Kamb method is based on the assumption that the data are statistically independent, a condition seldom met in structural work, and since the error within the structural measurements is neglected it can be concluded that the method does not completely eliminate statistical limitations of the data.

### Explanation of the Equal Area Net Projections (Fig. 23)

All the diagrams are lower hemisphere projections.

Upper Diagram: Scatter Diagram

Middle Diagram: Schmidt Method Contour Diagram; contour intervals as listed. Shading symbols = + lowest density; 1, 2, 3, . . . progressively higher densities; M = maximum

Lower Diagram: Kamb Method Contour Diagram; A = counter area, E = NA = number of points expected to fall within area A for a random distribution, SIG. = standard deviation, contour intervals = 0, 2, 4, 6, . . . standard deviations;

shading symbols: 1 = area with 2 SIG. density

2 = area with 4 SIG. density

3 = area with 6 SIG. density

4 = area with 8 SIG. density

" = " " " "

M = maximum

Fig. 24 is a hand contoured Schmidt plot of the same data as in the computer plot of Fig. 23. Note the similarity of the two plots by different methods.

Fig. 25 parts a and b are compilation equal area net projections. Only the higher density contours that appeared on the computer plots are shown and unless indicated by a (K) they represent the Schmidt plots rather than the Kamb plots.

Fig. 25a indicates a fan axis for  $S_1$  foliation and this is represented in the field by opposite dipping  $S_1$  planes (Fig. 6). The Kamb and Schmidt plots differ for  $L_1$  and  $L_2$ ; the Kamb plot gives a steeper plunge in both cases.



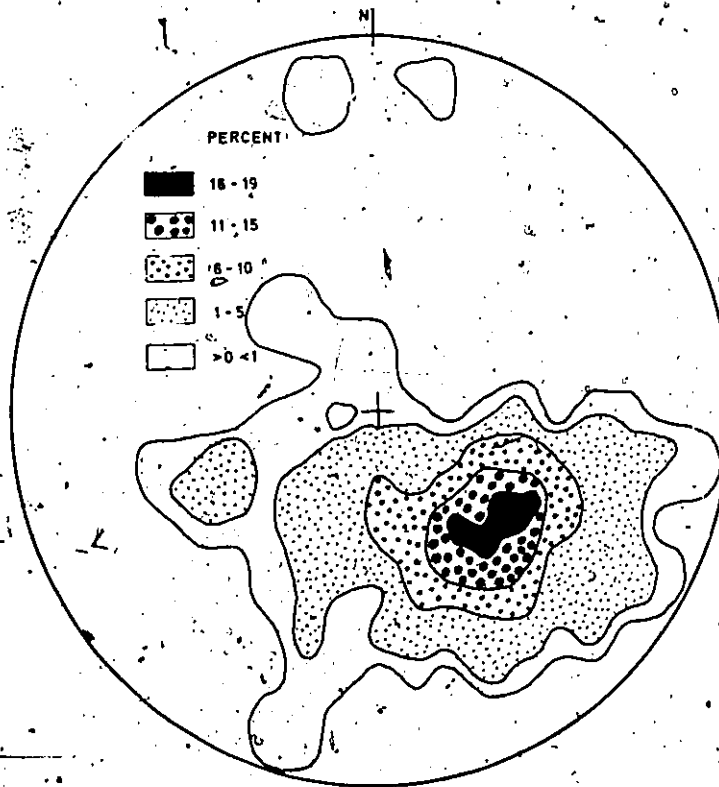
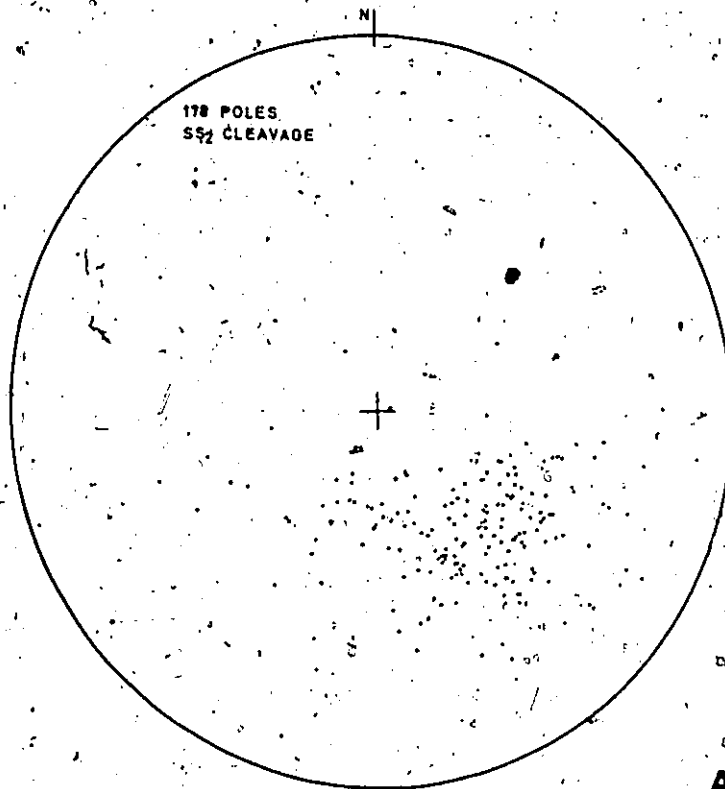


Fig. 24 Hand contoured equal area net. A) Scatter diagram, B) contoured diagram. The data is the same as that plotted in Fig. 23.

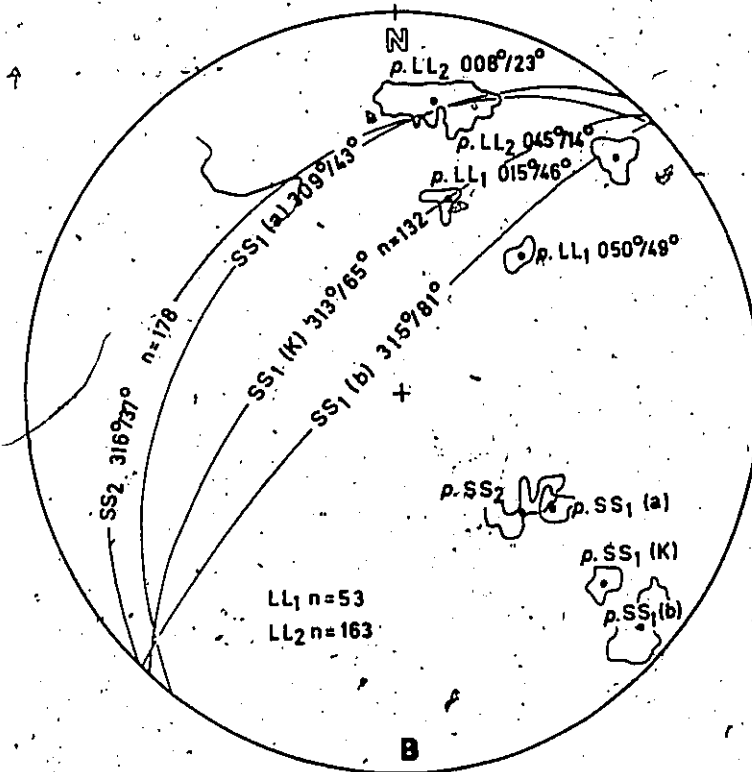
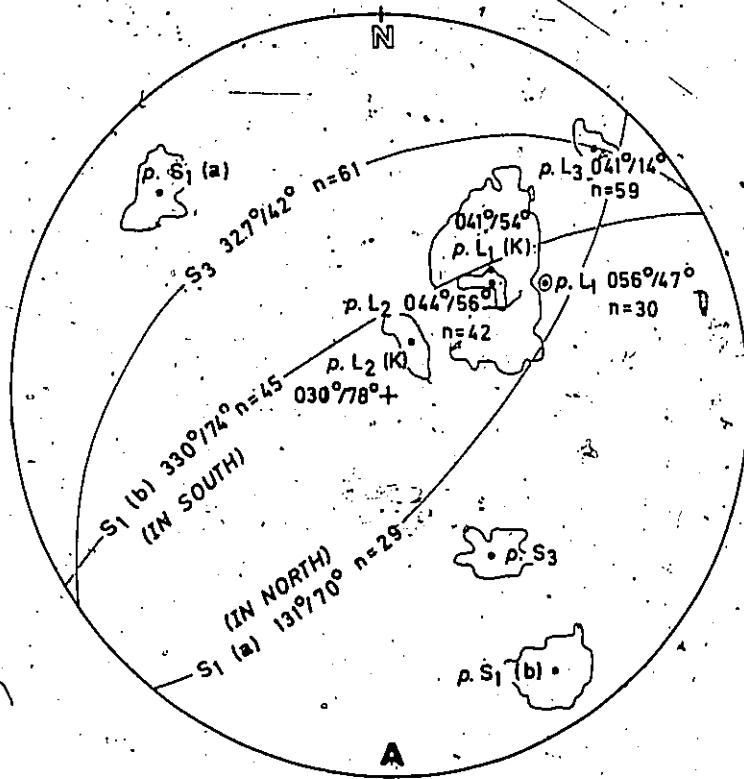


Fig. 25 Compilation equal area nets. Dominant modes from Schmidt plots unless indicated to be Kamb (K). A) Ascot Formation, B) St. Francis Group. n = sample size S<sub>1</sub> (a) S<sub>1</sub> (b) = two modes

Fig. 25b indicates double modes for  $LL_1$  and  $LL_2$  and these are due to the double mode of  $SS_1$  which appears in the Schmidt plots. The double mode of  $SS_1$  may not be due to two separate populations but rather to randomly distributed measurements as suggested by the single mode obtained by the Kamb plot.

In all cases the modal averages are based on only one reading, the most frequently occurring measurement, from any one outcrop in order not to bias the results.

APPENDIX III

ECONOMIC GEOLOGY

Introduction

The present study covers a large geographic area and, therefore the work would be incomplete if no mention of the economic minerals and construction materials was made. The following paragraphs briefly describe the metallic and non-metallic mineral showings (if any), as well as the construction materials, that were observed in the various rock units. Also, speculative comments in relation to the economic potential of the area are presented.

Cambro-Ordovician Rocks

During the latter part of the 19th century the Albert Mines - Eustis area (Fig. 1) in the Ascot Formation was a major base metal mining district of Canada. The last mine in the area closed during the early 1950's. Since then various types of exploration has been carried out without success. For a more detailed account of the various mine sites see Bancroft (1915), Stevenson (1937), Douglas (1941), Carrière (1954), St-Julien and Lamarche (1965), Lamarche (1970), and Sauvé, Cloutier and Genois (1972).

During the present study no sulphide showings other than pyrite were observed. However, veins several centimetres

thick of fibrous serpentine were observed within the ultramafic rocks (Fig. 5). The limited size of the outcrop area makes it rather doubtful that it is of any economic importance. Moreover the aeromagnetic maps (G. S. C., 1954d) do not indicate any lateral continuation of the ultramafics.

Within the Ascot Formation any metallic, or non-metallic mineral deposits that may be present will most likely not be located by surface mapping since these have been located and exploited. Geophysical surveys would be useful to determine whether the deposits exploited prior to the development of geophysical exploration techniques have additional reserves.

Several quarries are presently operating within the greenstones of the Ascot Formation. These produce crushed rock for road construction as well as the major constituent for asphalt pavement.

#### Middle and Upper Ordovician Rocks

No economic deposits have been found within the Magog Group or within the Sherbrooke and East Branch Pond Formations. Due to the types of rock present, its origin, the very low grade of metamorphism and the lack of intrusives to remobilize and concentrate any sulphides that may be present in very minor proportions it seems very unlikely that any metallic or non-metallic mineral deposits of economic importance exist in the Magog Group. Moreover, the aeromagnetic maps (G. S. C., 1954a; b and d) do not exhibit any magnetic highs that could

be related to buried iron rich base metal deposits.

### Siluro-Devonian Rocks

Placer gold is the only economic mineral that has been reported to exist within the part of the study area underlain by the Siluro-Devonian rocks of the St. Francis Group (Cooke, 1957 p. 33-34). During the present study cubic pyrite crystals was the only sulphide observed.

It is unlikely that any base metallic or non-metallic economic mineral deposits occur within the rocks of the St. Francis Group. The contacts between the granite and the sedimentary rocks of the St. Francis Group, where observed (rarely), are barren, as is the hornfelsic zone, of any sulphide showings. In these regions the sedimentary rocks must have been remobilized sufficiently to permit the concentration, near the heat source, of base metals had they existed in very minor amounts in the original rock. Also, the aeromagnetic maps (G. S. C., 1954a; c and d) do not exhibit any magnetic anomalies therefore buried iron rich sulphide deposits or mafic to ultramafic rocks are not present within the study area.

The placer gold, although not observed during the present study, may, however be present in sufficient quantities in some of the rivers and streams, particularly the Moe (Fig. 1), to be of minor importance (McGerrigle, in Cooke, 1957 p. 33). A systematic detailed geochemical study on the stream sediments may be useful in determining the source of the gold.

Several quarries are presently operating within the granitic plutons near Stanstead, Graniteville and Béebe (Fig. 1). The rock is used primarily for construction (see also Burton, 1931 and Cooke, 1950 p. 137-138).

### Pleistocene

For a detailed account of the Pleistocene geology, in part of the study area see McDonald 1967 and 1969.

Throughout the area very large Pleistocene sand and gravel deposits are present. Many of these have been opened to produce gravel for road construction, and concrete.

McDonald (1966) reported the presence of minor amounts of gold and silver within surface till in various localities, however no detailed exploration work has been done to determine whether or not economic amounts exist.

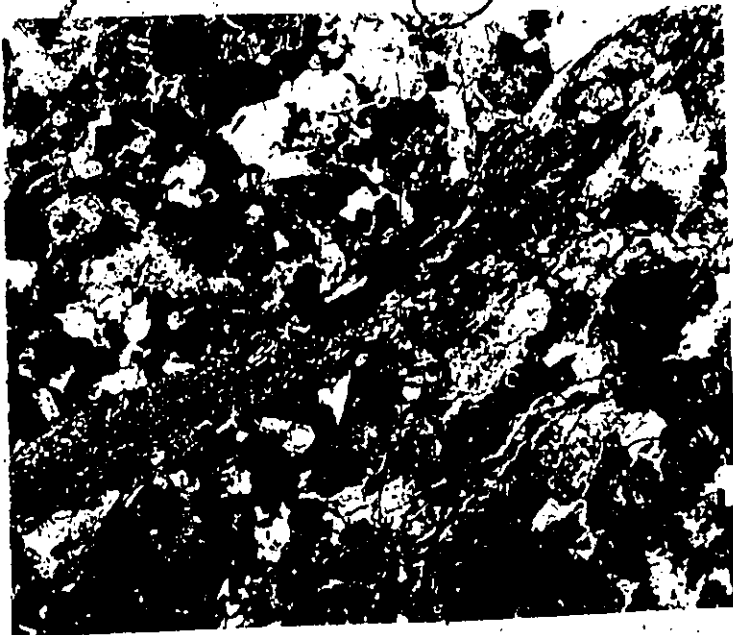
Plate I



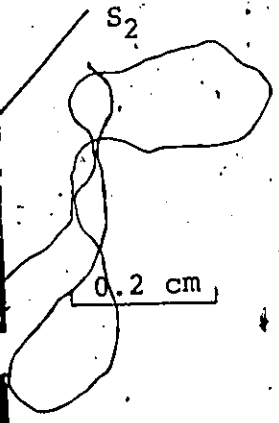
a)

0.2 cm

Photomicrograph; crossed nicols. Undeformed Upper or Middle Devonian granite (loc. K-1).



b)



Photomicrograph; crossed nicols. Lower Middle or Lower Ordovician granite with foliation, most probably  $S_2$  (loc. K-2).

Plate II

SE.



NW

a)

Bedding is well defined by a dolomite (light) layer in the uniform dark siliceous limestone.  $SS_1$  cleavage is parallel to bedding. Ayer's Cliff Member, St. Francis Group (loc. 28).



b)

Slump structures in calcareous siltstones truncated on one side thus indicating a primary structure; Barton River Member, St. Francis Group (loc. 13).

Plate III

SW

NE



a)

Flame structures in northwest dipping slates (dark) and siltstones (light) indicating overturning to the southeast; Barton River Member, St. Francis Group (loc. 153).

NW

SE



b)

Cross-bedding in northwest dipping calcareous siltstone beds indicates overturning to the southeast; Barton River Member, St. Francis Group (loc. 115).

Plate IV



0.2 cm

Photomicrograph; plane light of  $F_1$  folds defined by thin quartz-rich beds in tuffaceous (?) quartz-sericite rock; unit A2, Ascot Formation (loc. 326).  $S_1$  schistosity with aligned sericite is parallel to bedding on fold limbs and axial-planar to the folds.

Plate V

SE



NW

Steeply plunging  $F_2$  fold in  $S_1$  schistosity, quartz-sericite schist; unit A4, Ascot Formation. Axial plane is parallel to  $S_1$  schistosity.  $L_1$  lineation is defined by quartz ridges which curve obliquely around the  $F_2$  fold axis (loc. 139).

a)

SE



NW

$F_2$  fold in quartz vein and  $S_1$  schistosity in sericite-quartz phyllite; unit A4, Ascot Formation.  $S_2$  cleavage is not well developed (loc. 69).

b)

Plate VI

SE



NW

F<sub>2</sub> folds in quartz veins and parallel S<sub>1</sub> foliation, sericite-quartz schist; unit A4, Ascot Formation (loc. 71). S<sub>2</sub> cleavage is poorly developed.

a)

SE



NW

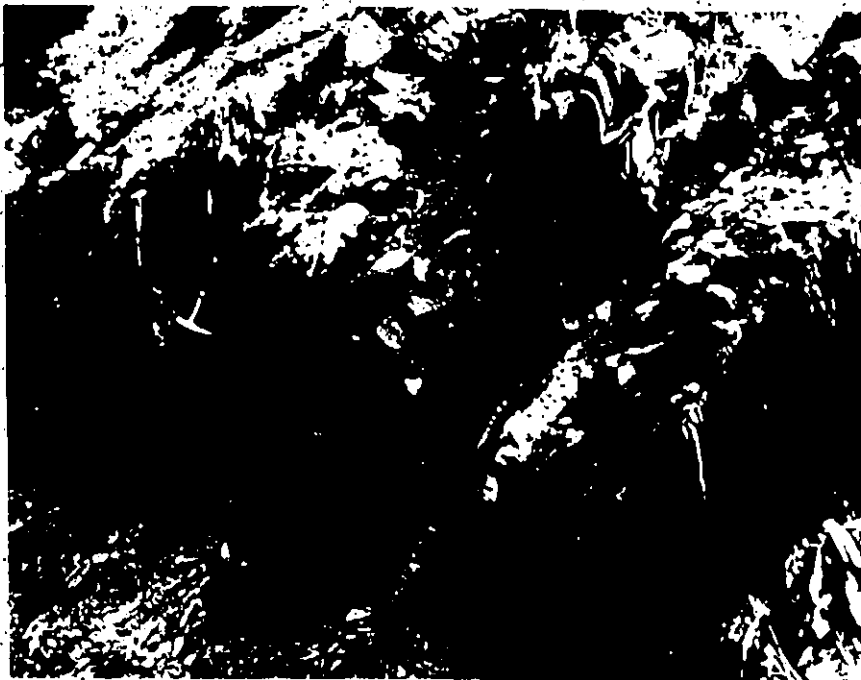
Photomicrograph; plane light of F<sub>2</sub> folds in fine sericite and quartz rich layers and parallel S<sub>1</sub> foliation; unit A4, Ascot Formation (loc. 66). S<sub>2</sub> crenulation cleavage is most apparent in the axial regions of the folds.

[ 0.2 cm ]

b)

Plate VII

NW



SE

S<sub>3</sub>

S<sub>0</sub>;S<sub>1</sub>(S<sub>2</sub>)

a) F<sub>3</sub> folds in bedding, S<sub>0</sub>, and parallel S<sub>1</sub>(S<sub>2</sub>) foliation. Sericite-quartz phyllite; unit A4, Ascot Formation (loc. 66). S<sub>3</sub> crenulation and fracture cleavage is axial-planar to the F<sub>3</sub> folds.

NW



SE

S<sub>3</sub>

0.2 cm

S<sub>0</sub>;S<sub>1</sub>

b)

b) Photomicrograph, plane light, of S<sub>3</sub> crenulation cleavage across S<sub>1</sub> foliation and bedding, S<sub>0</sub>. Quartz-sericite phyllite; unit A4, Ascot Formation (loc. 62).

Plate VIII

NW

SE



a)

S<sub>3</sub>

S<sub>0</sub>; S<sub>1</sub>

S<sub>3</sub> crenulation and slip cleavage across S<sub>1</sub> schistosity and parallel bedding, S<sub>0</sub>. Quartz-sericite phyllite; unit A3, Ascot Formation (loc. 213).

NW

SE



b)

Photomicrograph; plane light, of S<sub>3</sub> crenulation and slip cleavage across bedding, S<sub>0</sub>, and schistosity, S<sub>1</sub>. Graphitic phyllite; unit A4, Ascot Formation (loc. 317).

0.2 cm

Plate IX

SE



NW

Open  $F_3$  folds and  $S_3$  cleavage crossing vertical bedding,  $S_0$ , and schistosity,  $S_1$ . Sericite-quartz schist; unit A4, Ascot Formation (loc. 4).

$S_0; S_1$

$S_3$

a)

NW



SE

Photomicrograph, plane light, of open  $F_3$  fold and crenulation cleavage. Quartz-sericite phyllite; unit A4, Ascot Formation (loc. 2). A possible  $F_1$  or  $F_2$  fold outlined by calcite is in the upper right-hand corner.

0.2 cm

b)

$S_3$

$S_0; S_1$

Plate X

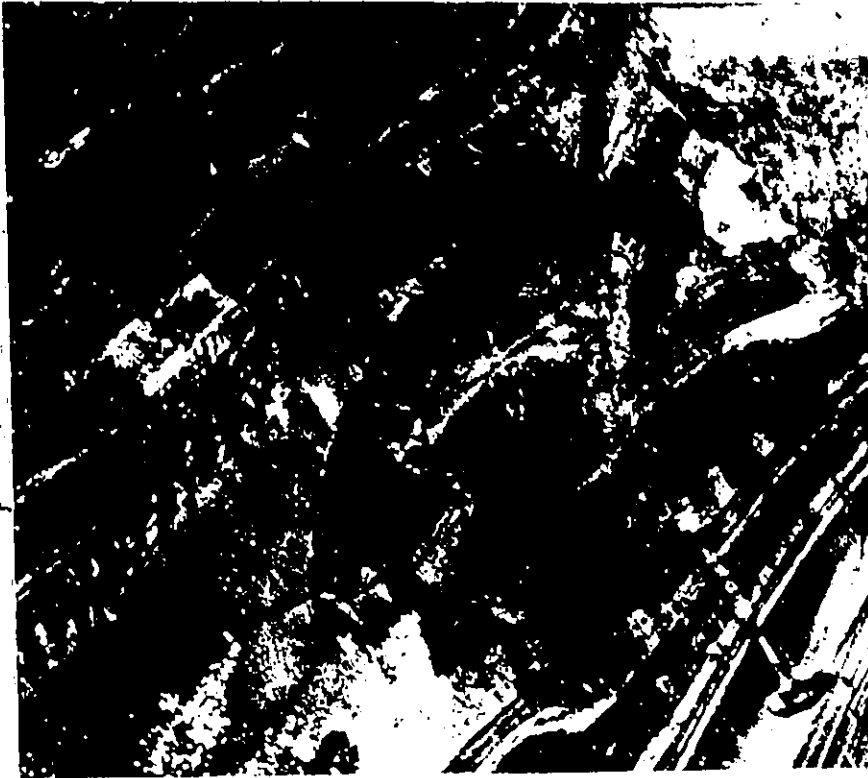


Subvertical  $F_2$  fold hinge refolded by an open recumbent  $F_3$  fold. Sericite-quartz phyllite; unit A4, Ascot Formation (loc. 66).

Plate XI

SW

NW



a)

FF<sub>1</sub> folds defined by a dark fine micaceous quartz rich bed in siliceous limestone; Ayer's Cliff Member, St. Francis Group (loc. 53).



b)

Photomicrograph; crossed nicols, of FF<sub>1</sub> (?) fold hinge in a calcite grain; Ayer's Cliff Member, St. Francis Group (loc. 53).

0.05 cm

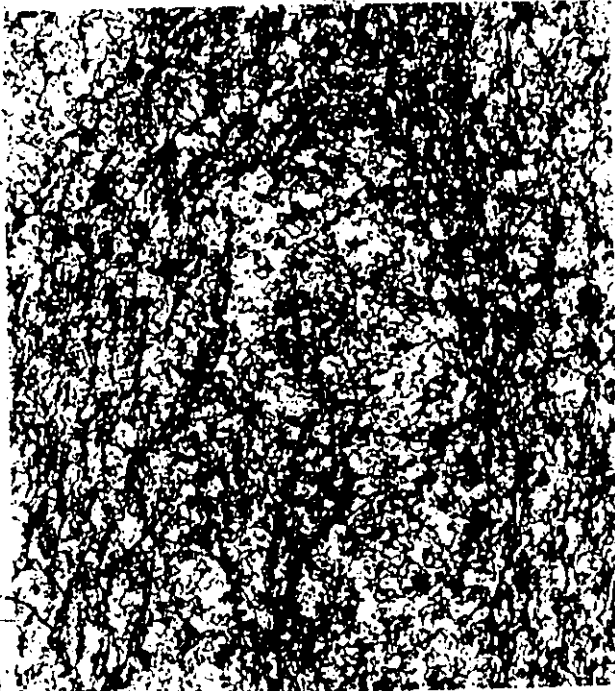
Plate XII



a)

Photomicrograph; plane light of FF<sub>1</sub> intrafolial folds in quartz rich layering in siliceous limestone; unit F2, Ayer's Cliff Member, St. Francis Group (loc. 40). SS<sub>1</sub> cleavage is parallel to the fold limbs.

0.2 cm



b)

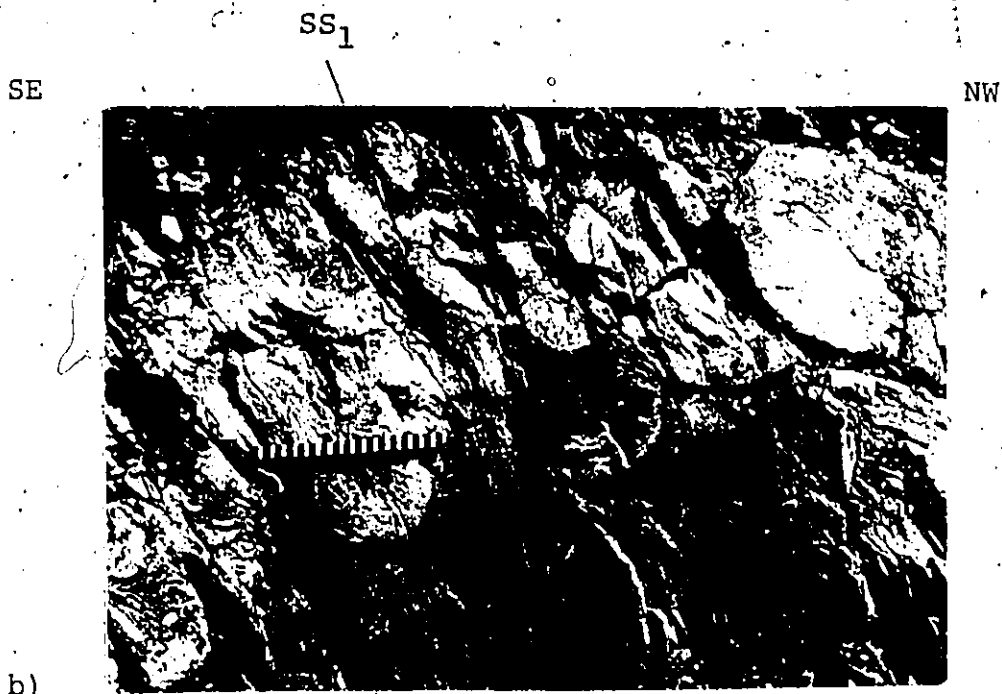
Photomicrograph, plane light. An enlargement of FF<sub>1</sub> fold above. Note the anastomosing nature of the SS<sub>1</sub> cleavage.

0.1 cm

Plate XIII



FF<sub>1</sub> folds in calcareous silty slate (dark) and quartz siltstones (light). Steeply dipping SS<sub>1</sub> fracture and slaty cleavage is axial-planar to FF<sub>1</sub>. An open FF<sub>2</sub> fold crosses steep limb in upper right corner with low dipping SS<sub>2</sub> axial-plane fracture and crenulation cleavages. Westmore Member, St. Francis Group (loc. 185).



An enlargement of the lower right corner of (a) above. Fold mullion-like structures, on lower surface of quartz siltstone bed, in antiformal hinge zone. Cusps from underlying calcareous silty slate protrude into the more competent quartz siltstone. Scale units are cm.

Plate XIV



FF<sub>1</sub> fold in hornfelsic siltstone. SS<sub>1</sub> cleavage is parallel to bedding, SS<sub>0</sub>, except in the hinge region (loc. between St. Hermenegilde and Villette, east of the study area (see Fig. 4)).



Bedding, SS<sub>0</sub>, and SS<sub>1</sub> slaty cleavage in calcareous slate; Ayer's Cliff Member, St. Francis Group (loc. 16).

Plate XV.

NW

SE



40 cm

Bedding,  $SS_0$ , nearly vertical and gently dipping  $SS_1$  fracture cleavage in slate (dark) and siltstone (light). Westmore Member, St. Francis Group (loc. 237).  $LL_1$  lineations are represented as a colour banding.

Plate XVI

SS<sub>0</sub>;SS<sub>1</sub>

SS<sub>2</sub>

NW

SE



a)

SS<sub>2</sub> fracture cleavage developed in argillaceous rock (centre) and not in calcareous sandstone; Ayer's Cliff Member, St. Francis Group (loc. 35). SS<sub>1</sub> cleavage is parallel to bedding, SS<sub>0</sub>.

SS<sub>0</sub>

SE

NW

SS<sub>2</sub>

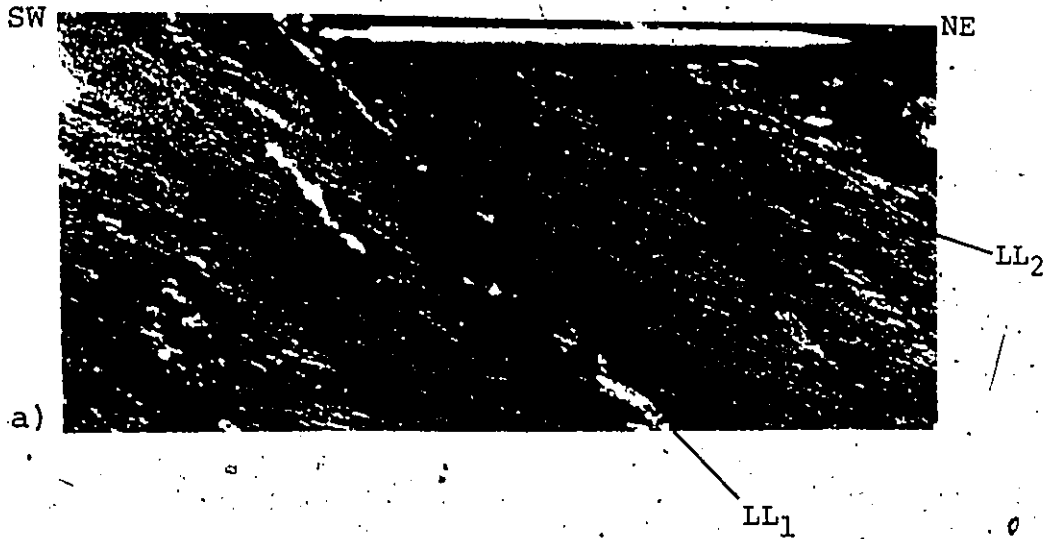
SS<sub>1</sub>



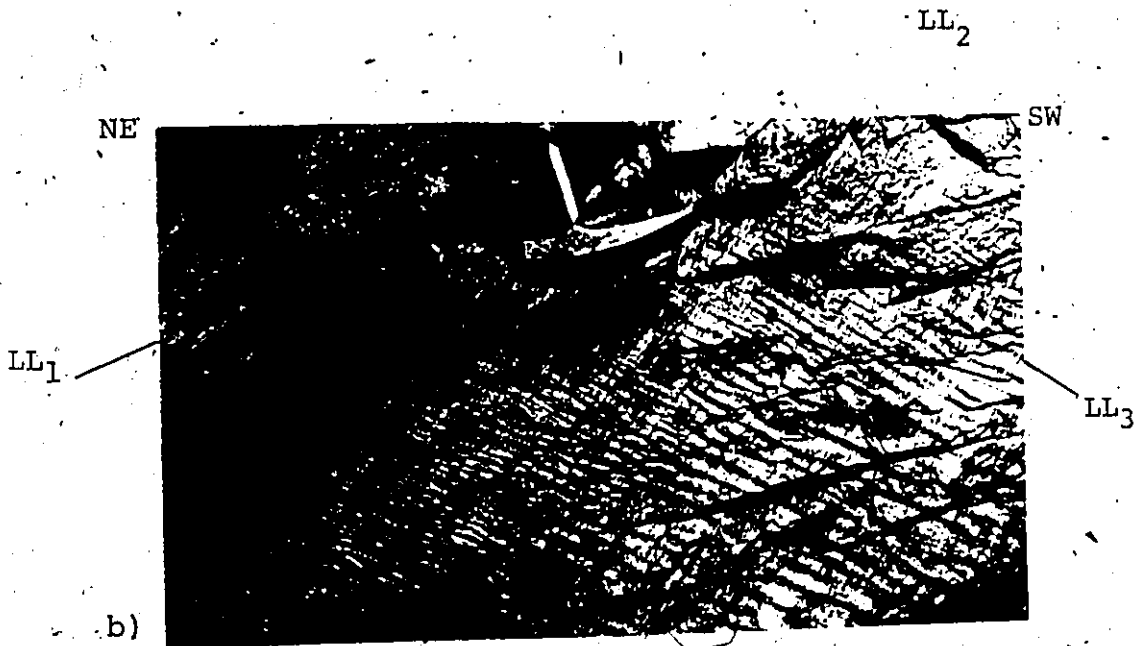
b)

SS<sub>1</sub> slaty and fracture cleavage, followed by calcite veins, refracted towards the normal to bedding, SS<sub>0</sub>, in going from the calcareous silty slate (right) to the quartz siltstone (left). Westmore Member, St. Francis Group (SE margin of Plate XIII, loc. 185). The calcite veins in the calcareous silty slate have been crenulated by SS<sub>2</sub>. The SS<sub>2</sub> cleavage in the calcareous silty slate (right) is parallel to SS<sub>1</sub> in the quartz siltstones (left). Scale units are cm.

Plate XVII

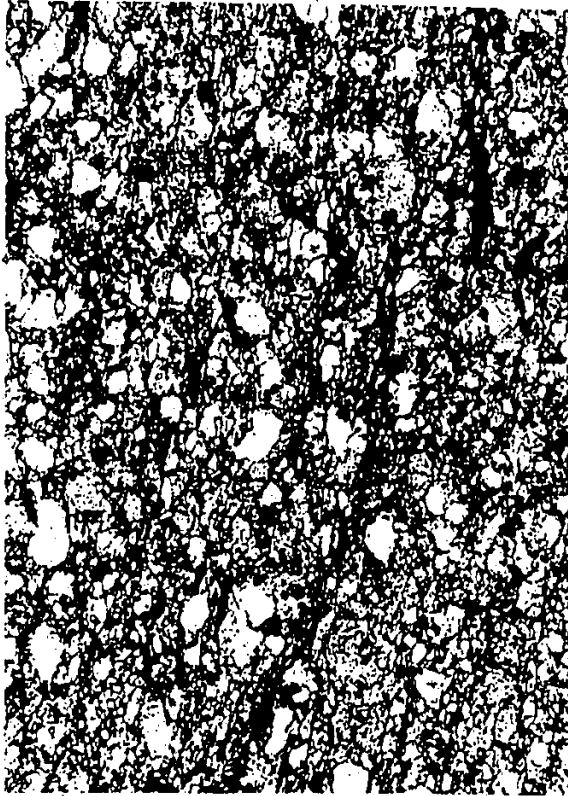


Lineations, LL<sub>1</sub> colour banding and LL<sub>2</sub> crenulations, on SS<sub>1</sub> cleavage surface in calcareous phyllite. Ayer's Cliff Member, St. Francis Group (loc. 33).



Lineations, LL<sub>1</sub> colour banding, LL<sub>2</sub> crenulations, and LL<sub>3</sub> crenulations with steep axial planes, on SS<sub>1</sub> cleavage surfaces in phyllite and siltstone. Barton River Member, St. Francis Group (loc. 19).

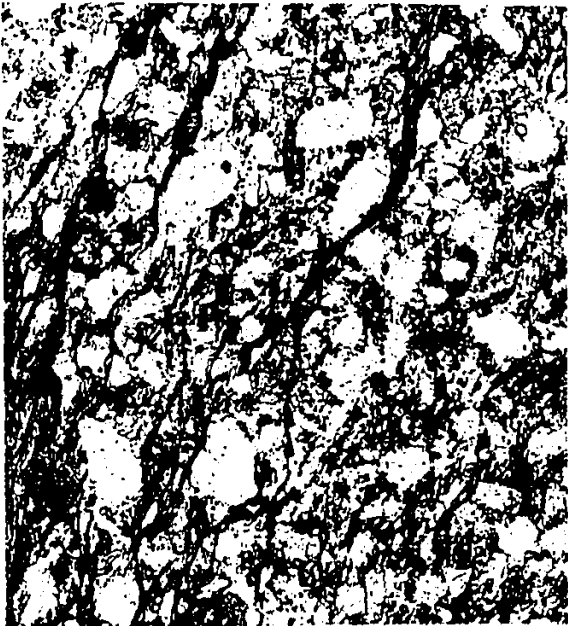
Plate XVIII



a)

Photomicrograph, plane light. Anastomosing SS<sub>1</sub> cleavage in quartz siltstone. Westmore Member, St. Francis Group (loc. 237).

0.04 cm



b)

Photomicrograph, plane light. Anastomosing SS<sub>1</sub> cleavage in micaceous quartz sandstone. Sericite is aligned parallel to the SS<sub>1</sub> cleavage planes. Barton River Member, St. Francis Group (loc. 225).

0.1 cm

Plate XIX

SE

NW



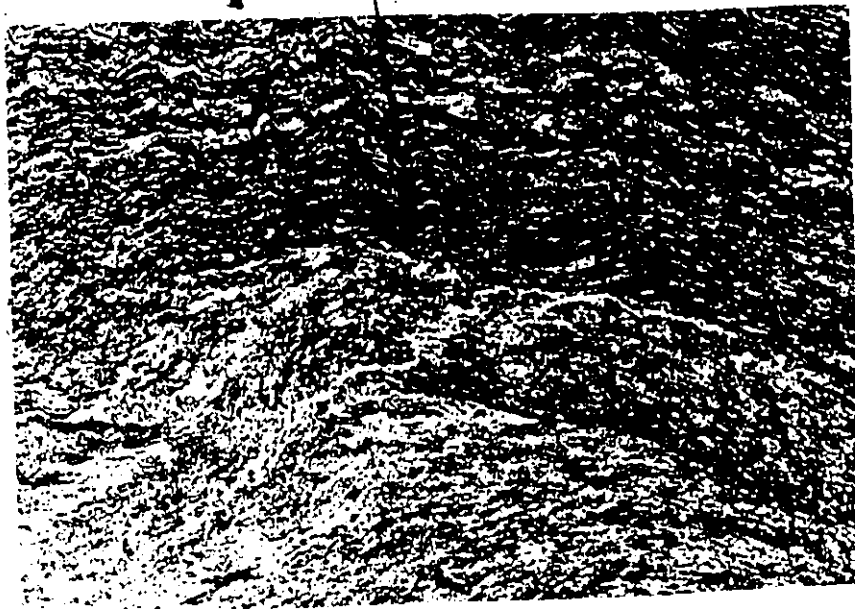
FF<sub>2</sub> folds affecting bedding, SS<sub>0</sub>, and cleavage, SS<sub>1</sub>, in siliceous limestone (light) and calcareous phyllite (dark); Ayer's Cliff Member, St. Francis Group (loc. 34). SS<sub>2</sub> crenulation and fracture cleavage is axial-planar. Scale units are cm.

SS<sub>0</sub>;SS<sub>1</sub>

SS<sub>2</sub>

a)

SS<sub>2</sub>



SS<sub>0</sub>;SS<sub>1</sub>

0.2 cm

b)

Photomicrograph, plane light. Bedding, SS<sub>0</sub>, and cleavage, SS<sub>1</sub>, folded by FF<sub>2</sub> in calcareous phyllite (dark) and calcareous siltstone (light); Barton River Member, St. Francis Group (loc. 205). SS<sub>2</sub> crenulations and fractures are present in the axial region of the fold.

Plate XX

NW



SS<sub>0</sub>  
SS<sub>1</sub>

SS<sub>2</sub>

a)

SE

SS<sub>1</sub> slaty cleavage and calcite veins parallel to bedding, SS<sub>0</sub> in dark gray siliceous limestone. SS<sub>2</sub> fracture and crenulation cleavage obliquely cross-cuts SS<sub>0</sub> and SS<sub>1</sub>; Ayer's Cliff Member, St. Francis Group (loc. 41). Scale units are cm.

NW



SS<sub>2</sub>

SS<sub>1</sub>

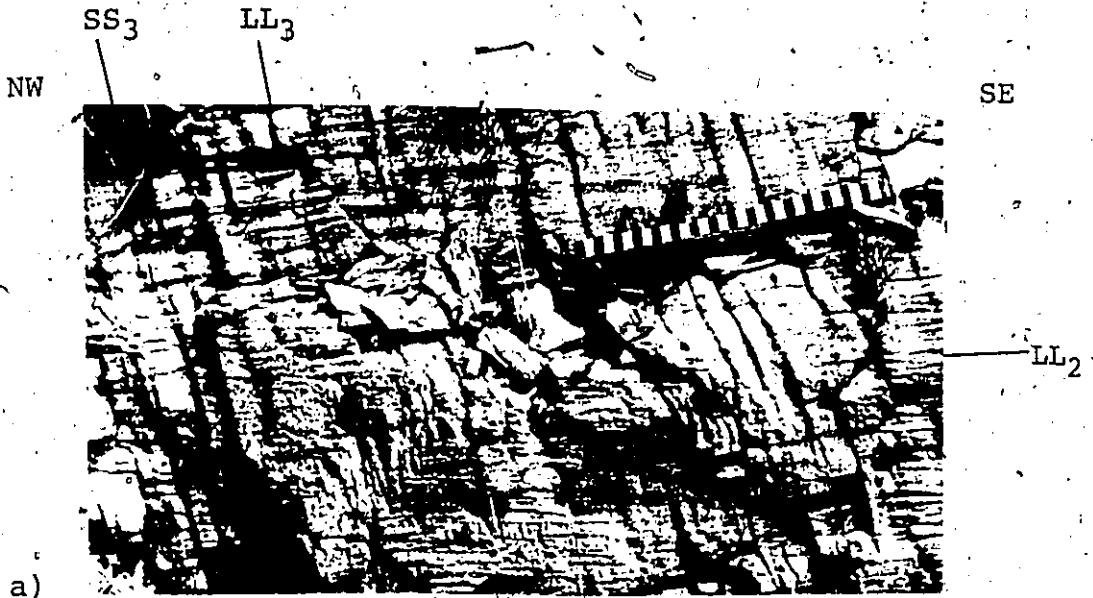
b)

SE

Photomicrograph, plane light. SS<sub>1</sub> slaty cleavage in calcareous phyllite is crossed by SS<sub>2</sub> crenulated cleavages; Westmore Member, St. Francis Group (loc. 259).

0.2 cm

Plate XXI

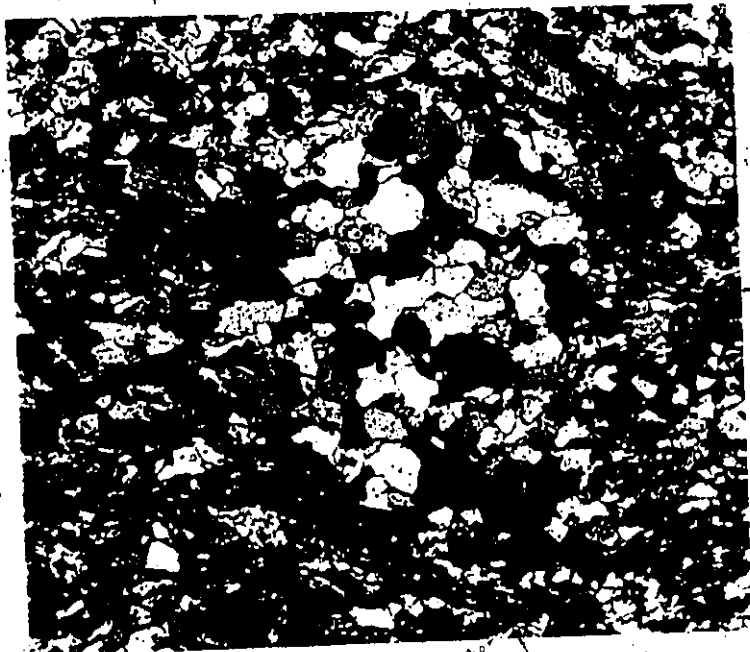


LL<sub>3</sub> and LL<sub>2</sub> crenulation lineations on nearly vertical SS<sub>1</sub> cleavage in phyllite. SS<sub>3</sub> cleavage is nearly vertical; Barton River Member, St. Francis Group (loc. 14). Scale units are cm.



Photomicrograph, crossed nicols. Calcite infillings in pressure shadows next to calcite grain in siliceous limestone is elongated parallel to SS<sub>1</sub> cleavage; Ayer's Cliff Member, St. Francis Group (loc. 53).

Plate XXII



a)

Photomicrograph, crossed nicols, of triple junctions in quartz grains.  $SS_1$  cleavage curves around the large cluster of quartz grains; Ayer's Cliff Member, St. Francis Group (loc. 131).



b)

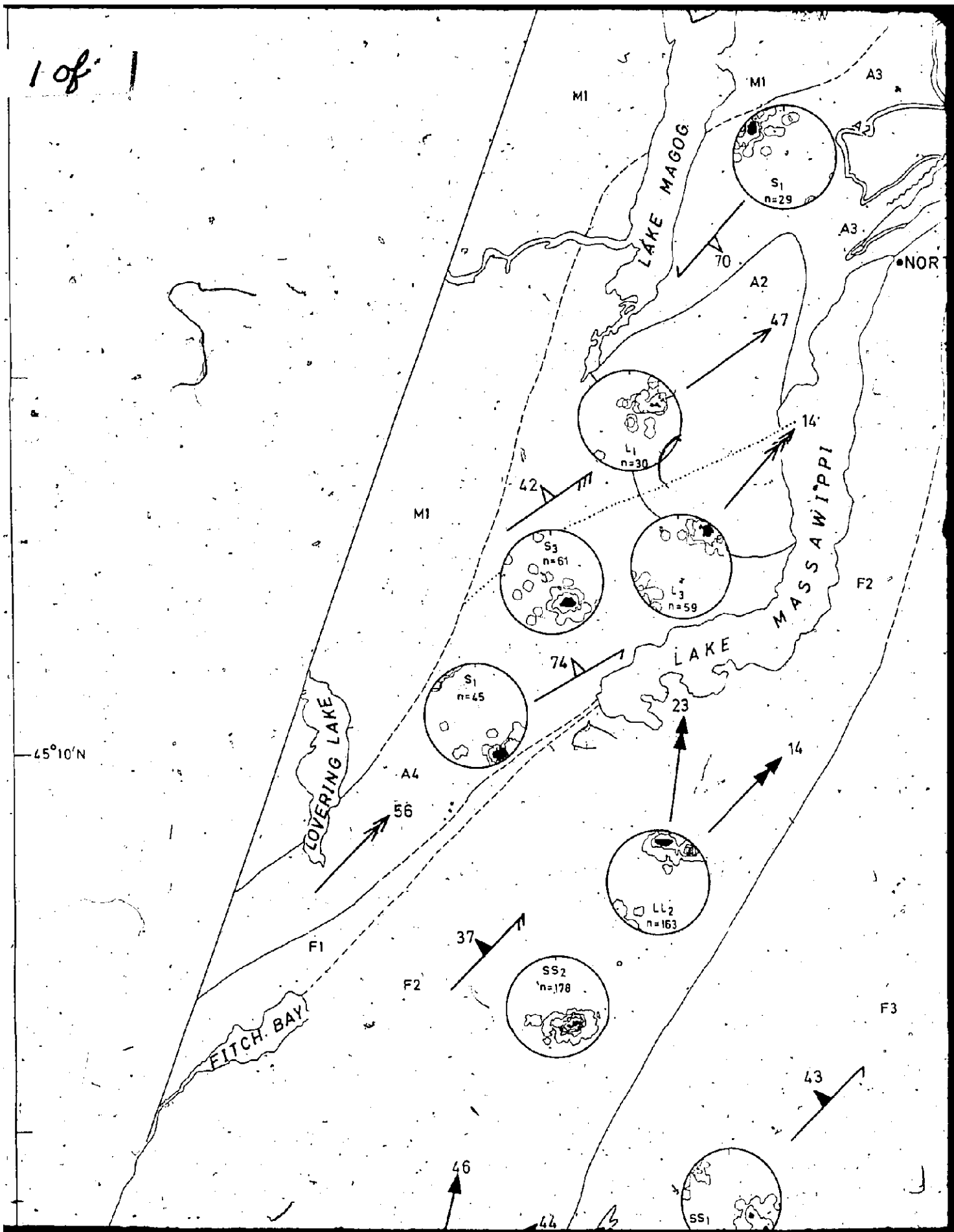
Photomicrograph, plane light, of random post-deformation biotite grains in hornfelsic siltstone cross-cut and include the cleavage,  $SS_1$ ; Barton River Member, St. Francis Group (loc. 105).

Plate XXIII



Bedding, GS<sub>0</sub>, and slaty cleavage, GS<sub>1</sub>, in dark slates; Glenbrooke Group. (Loc. south of Sargent's Bay, Lake Memphremagog). Scale units are centimetres.

1 of 1



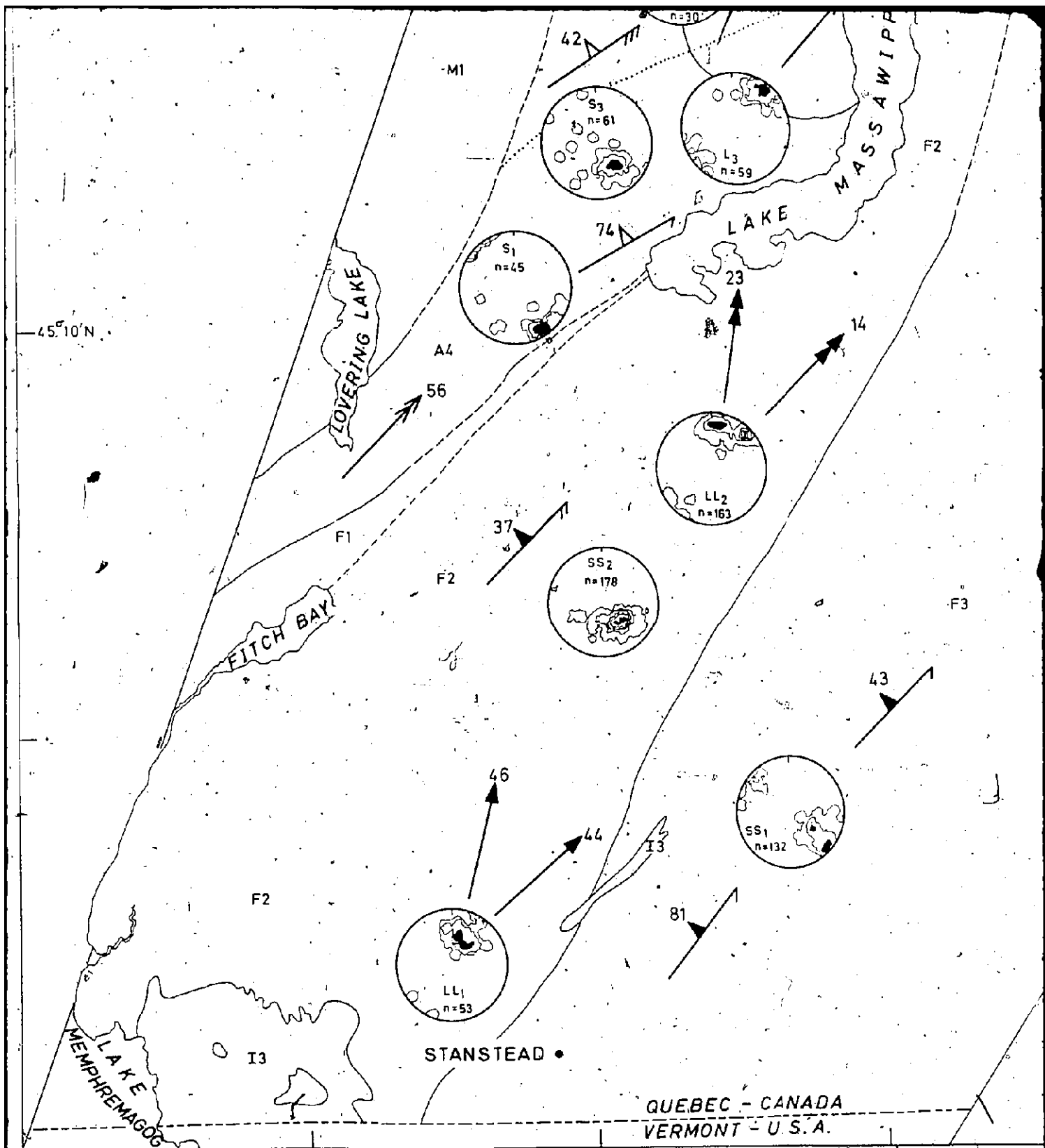
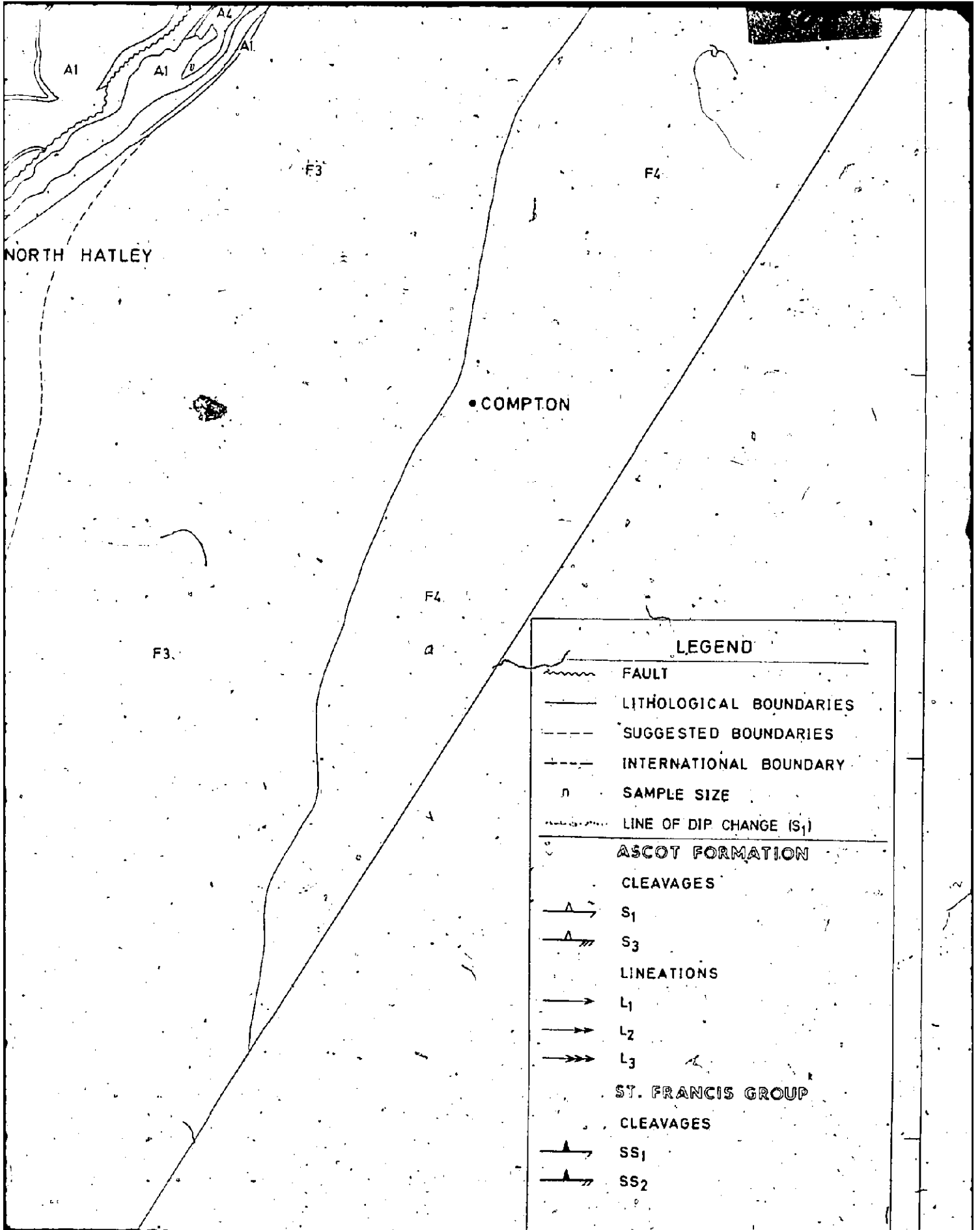













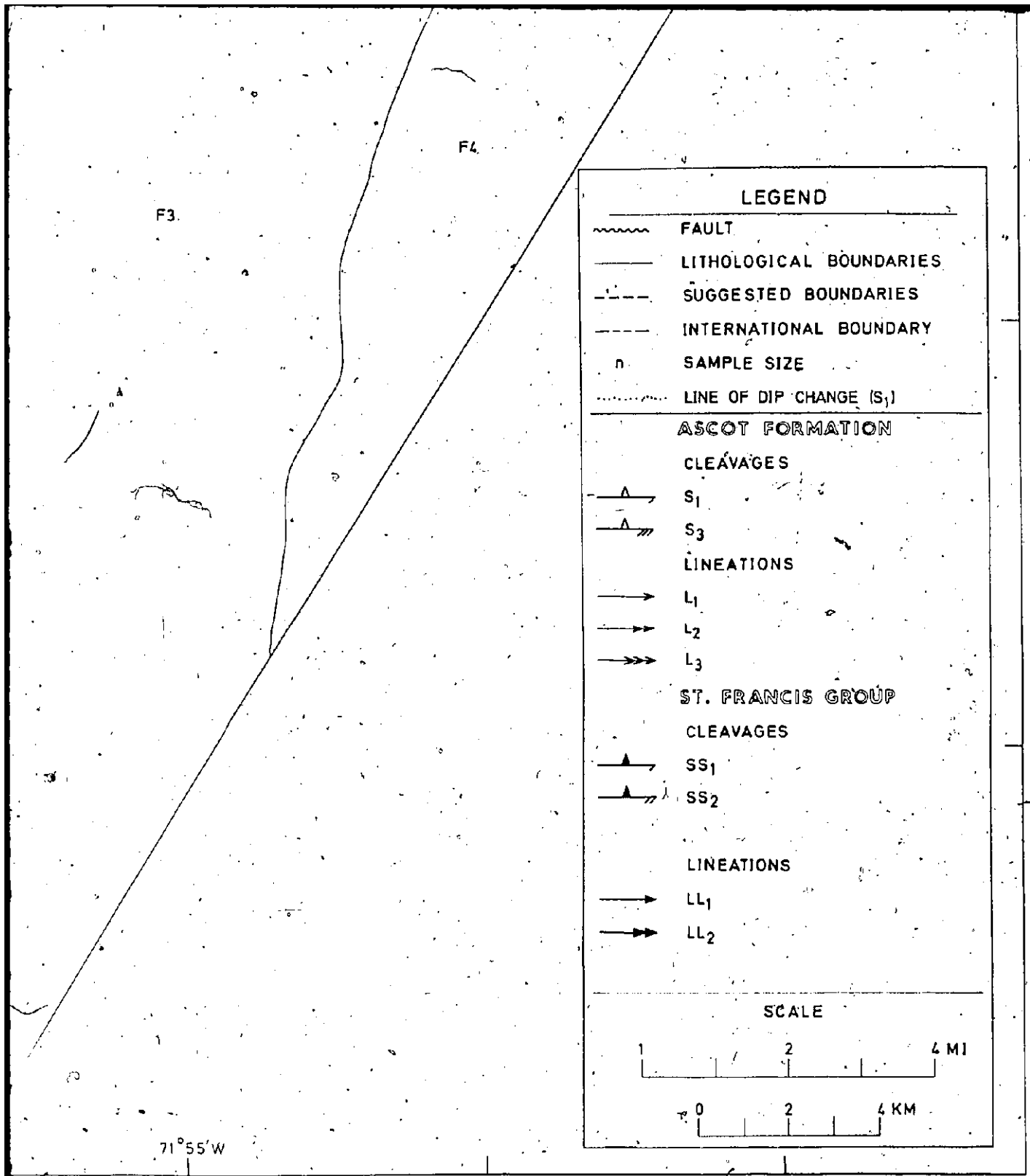


Fig. 7 Map of the Lake Massawippi area with equal area ne lineations and cleavages. Lithological units are numbered



**LEGEND**

-  FAULT
-  LITHOLOGICAL BOUNDARIES
-  SUGGESTED BOUNDARIES
-  INTERNATIONAL BOUNDARY
-  n SAMPLE SIZE
-  LINE OF DIP CHANGE (S<sub>1</sub>)
- ASCOT FORMATION**
- CLEAVAGES**
-  S<sub>1</sub>
-  S<sub>3</sub>
- LINEATIONS**
-  L<sub>1</sub>
-  L<sub>2</sub>
-  L<sub>3</sub>
- ST. FRANCIS GROUP**
- CLEAVAGES**
-  SS<sub>1</sub>
-  SS<sub>2</sub>



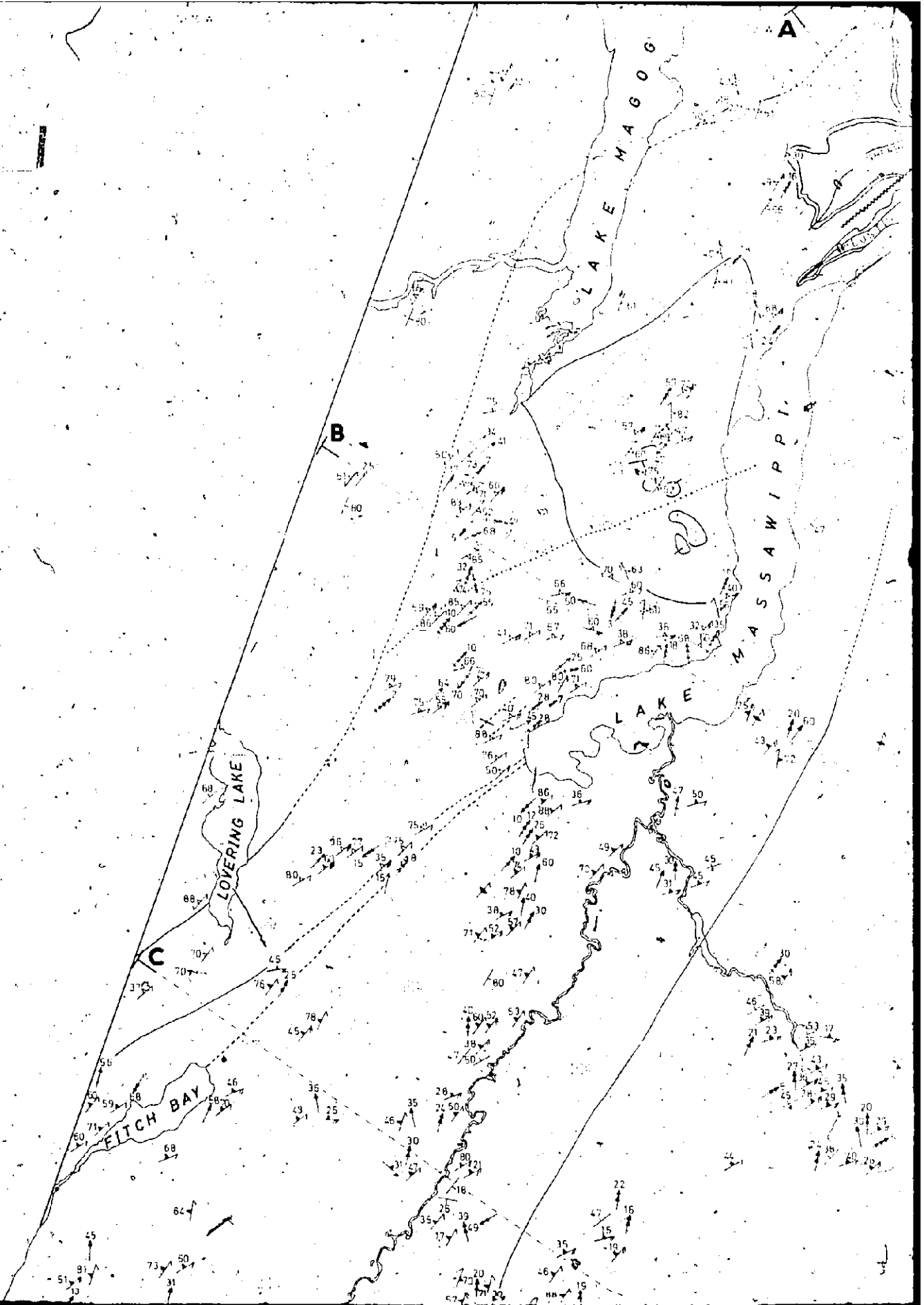
net projections and modal average orientations of ...  
 are as in Fig. 5.

4 of 4

1 of

45° 15' N

45° 05' N



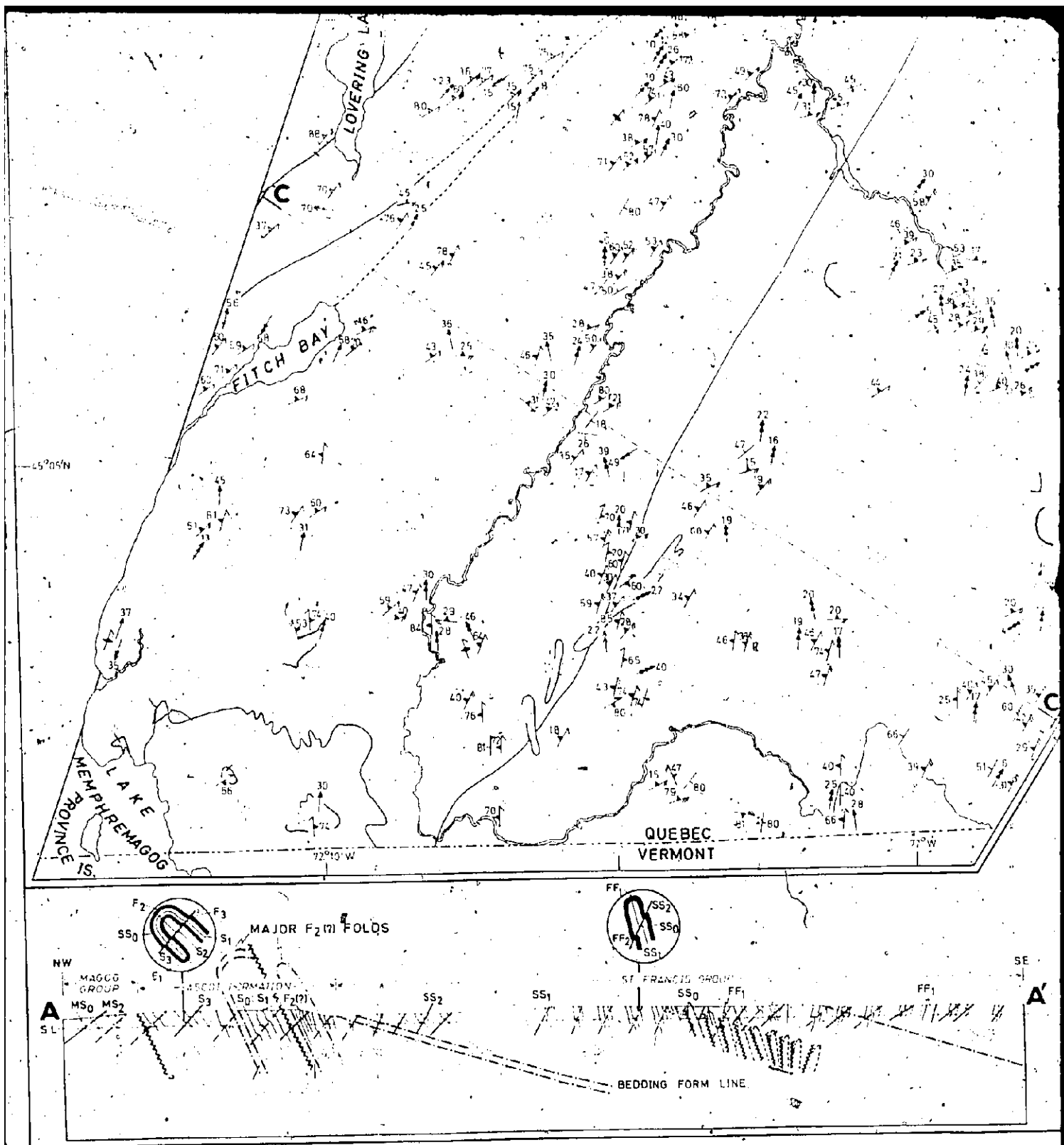
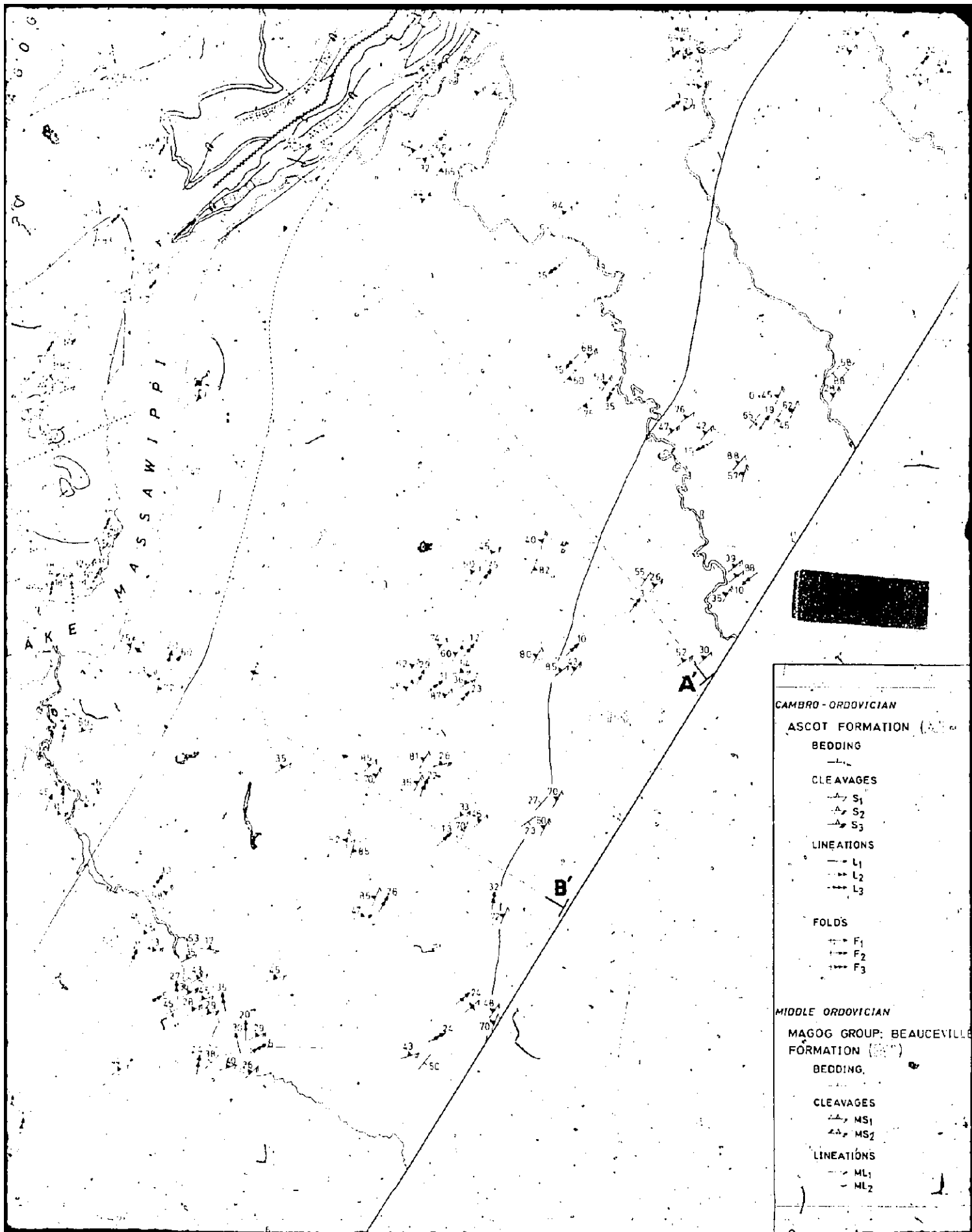
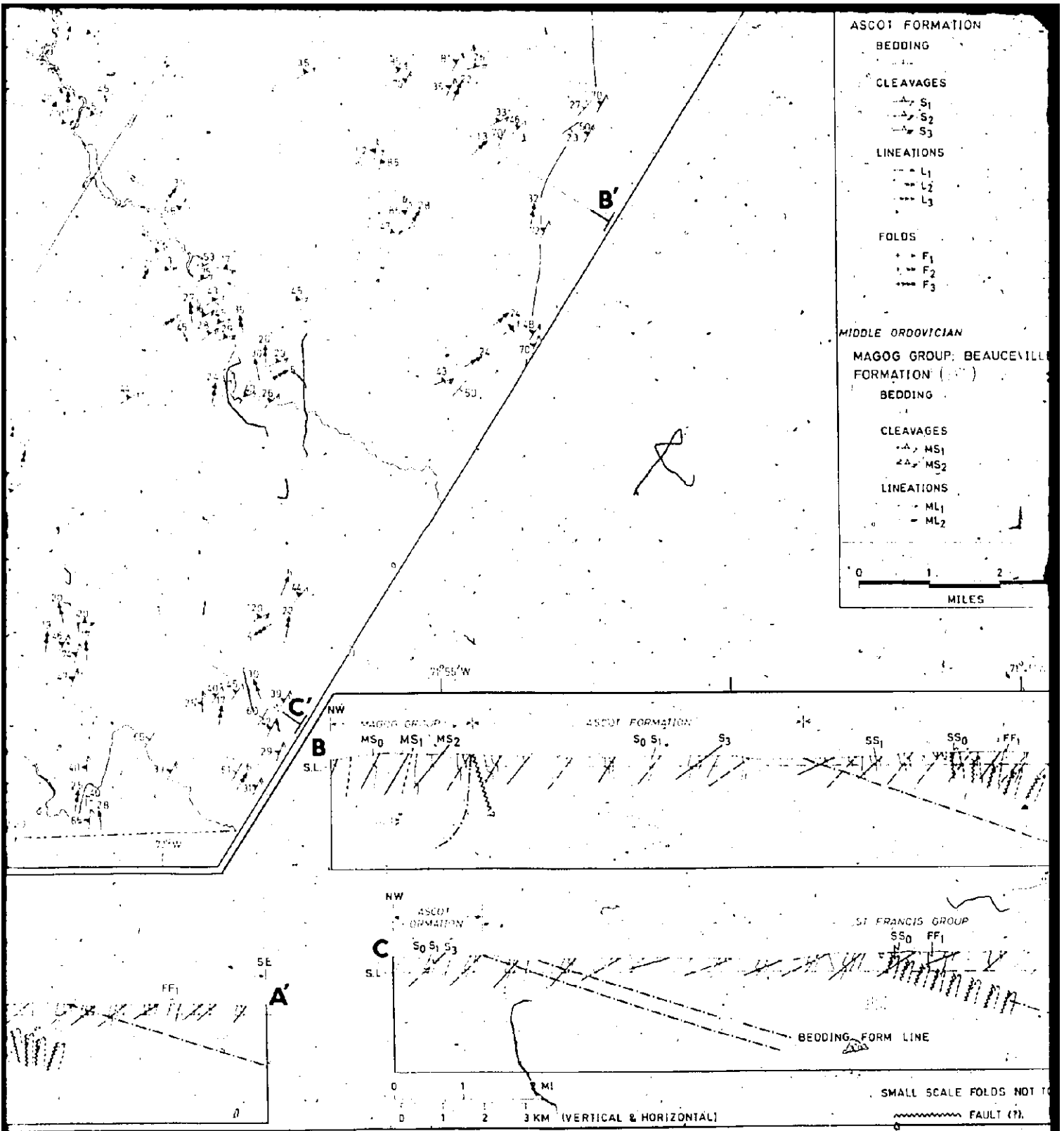
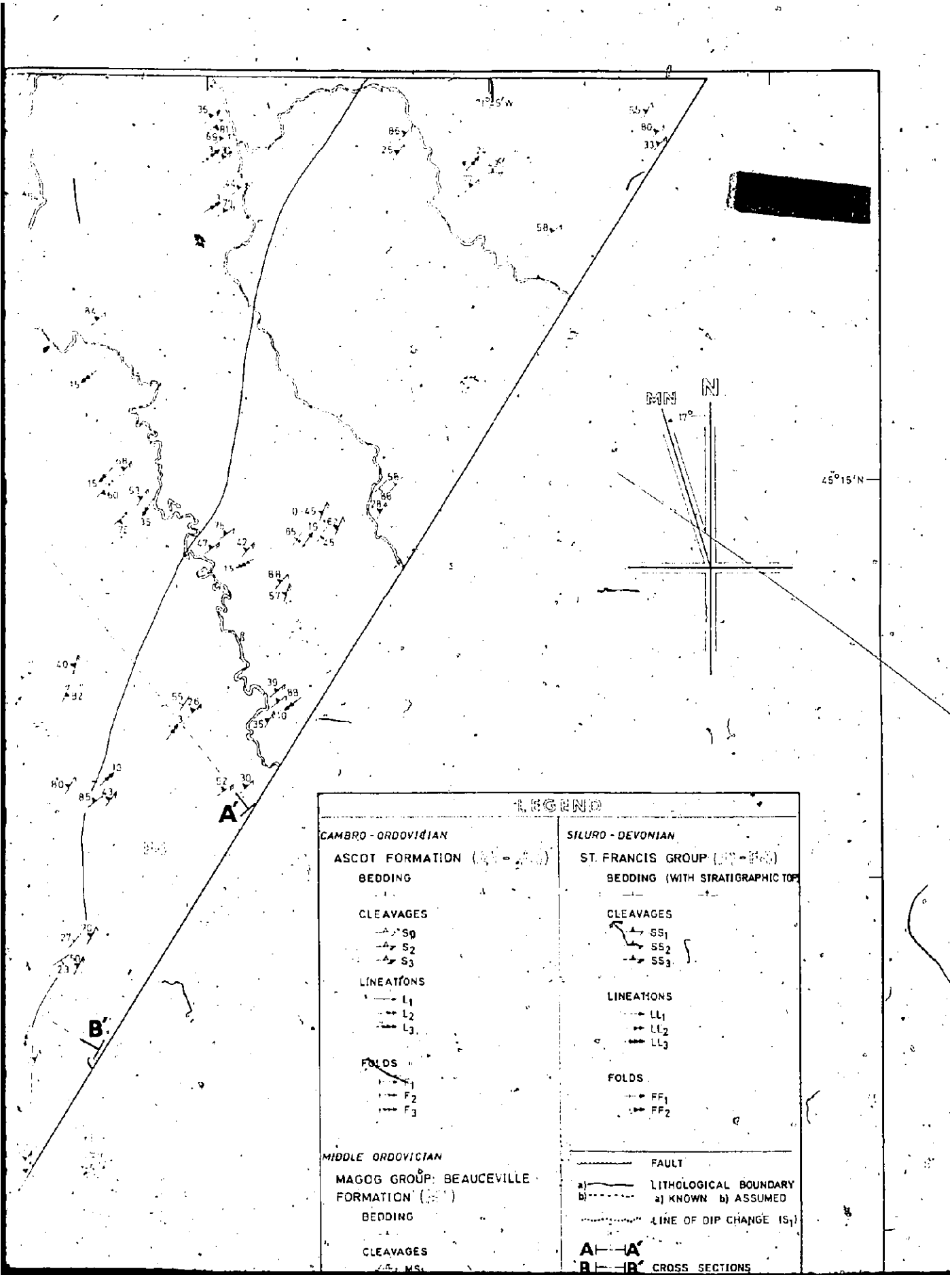


Fig. 6 Detailed structural map and cross sections as in Fig. 5. The major  $F_2$ (?) folds are interpreted only shown where they are not parallel to first



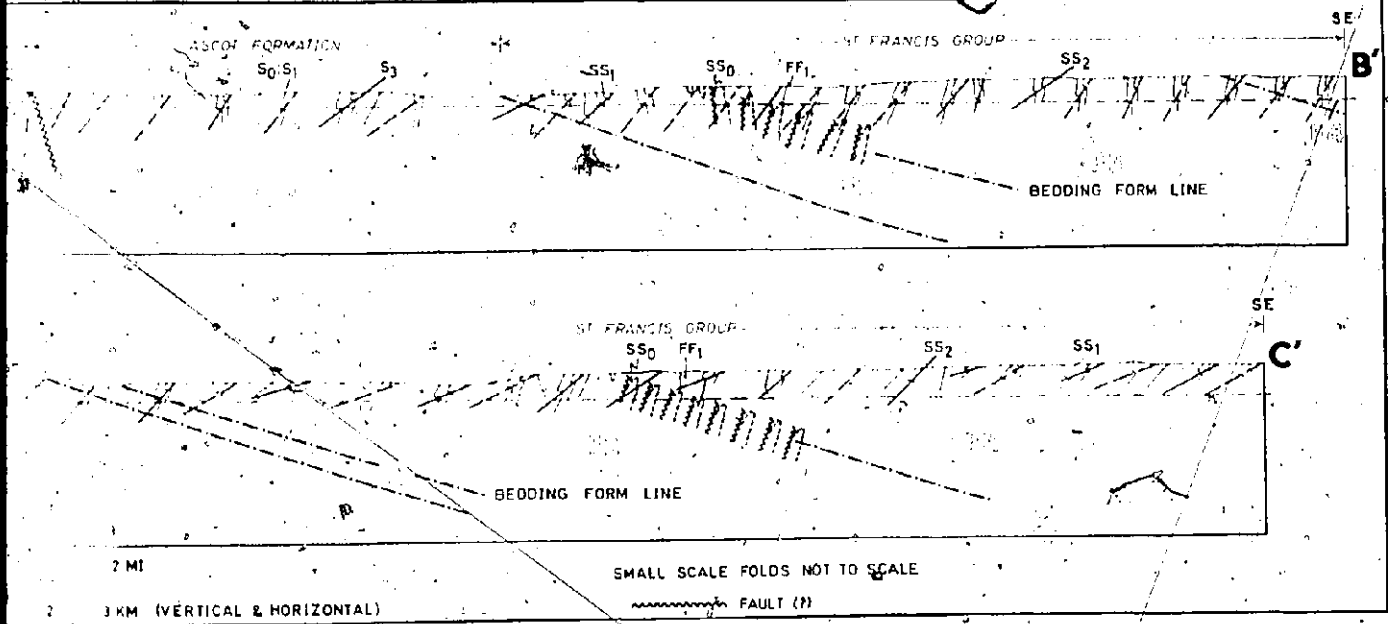
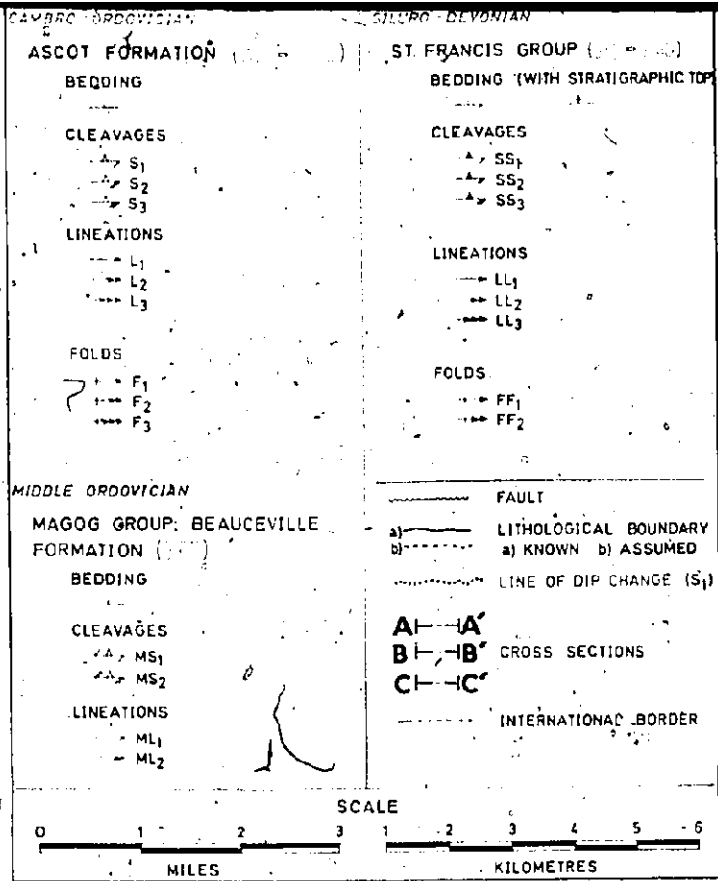


Geological map and cross sections of the Lake Massawippi area. The rock units are labelled. F<sub>2</sub>(?) folds are interpreted from St-Julien and Lamarche (1965). The bedding symbols are not parallel to first cleavages (S<sub>1</sub> and SS<sub>1</sub>).



**LEGEND**

CAMBRO-ORDOVICIAN	SILURO-DEVONIAN
<b>ASCOT FORMATION (A1 - A3)</b> BEDDING CLEAVAGES S <sub>1</sub> S <sub>2</sub> S <sub>3</sub> LINEATIONS L <sub>1</sub> L <sub>2</sub> L <sub>3</sub> FOLDS F <sub>1</sub> F <sub>2</sub> F <sub>3</sub>	<b>ST. FRANCIS GROUP (S1 - S3)</b> BEDDING (WITH STRATIGRAPHIC TOP) CLEAVAGES SS <sub>1</sub> SS <sub>2</sub> SS <sub>3</sub> LINEATIONS LL <sub>1</sub> LL <sub>2</sub> LL <sub>3</sub> FOLDS FF <sub>1</sub> FF <sub>2</sub>
<b>MIDDLE ORDOVICIAN</b> <b>MAGOG GROUP: BEAUCEVILLE FORMATION (M1)</b> BEDDING CLEAVAGES MS <sub>1</sub>	FAULT a) LITHOLOGICAL BOUNDARY b) KNOWN b) ASSUMED LINE OF DIP CHANGE (S <sub>1</sub> ) <b>A1 - A1'</b> <b>B1 - B1'</b> CROSS SECTIONS



Mississippi area. The rock units are labelled  
 and Lamarche (1965). The bedding symbols  
 and SS1).

