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GEOLOGY AND GEOCHEMISTRY OF TALC DEPOSITS
IN THE MADOC AREA, ONTARIO

by

GEORGE J. SIMANDL

~~B.Sc. (Spec. Geol.)~~, Concordia University, 1978

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of the requirements
for the degree of
Master of Science

Department of Geology
Carleton University
Ottawa, Ontario
November, 1984

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ABSTRACT

The Henderson talc deposit is located within Hastings metamorphic "low". It is one of the widest known sections of a main talc horizon, which is hosted by tremolitic, micaceous, dolomitic marble belonging to the Grenville Supergroup. It is a deformed tabular body over 250 m long, 7 to 25 m thick, at least 250 m deep, open at depth, striking 42° and dipping 65° to 85° NW. Talc ore is unusually white. Brightness of dry ore milled to -325 mesh is 95 to 96 on the 100 unit scale under green filter, making the ore suitable for a wide variety of industrial applications.

The ore consists mainly of talc (over 70%), dolomite (24%), serpentine (2 to 3%), phlogopite (2%) and tremolite (less than 1%). The core of the deposit is coarse grained, richer in talc and it has a higher MgO/CaO ratio than peripheral fine-grained ore.

The Henderson deposit was traditionally regarded as a vein type deposit; however, structural stratigraphic, petrological, mineralogical and geochemical investigation in conjunction with known regional tectonic history indicate that at least a portion of the ore could have been either precipitated on the sea-floor or derived by diagenesis and/or low grade metamorphism from magnesium rich sediments. Unusually high talc content and high MgO/CaO ratio and absence of calcite within the ore exclude the possibility that "Normal" prograde regional metamorphism of siliceous dolostone was the sole talc-forming process involved in the formation of the deposit.

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TABLE OF CONTENTS

	Page
Abstract	i
Acknowledgements	ii
Table of Contents	iii
List of Tables	vi
List of Figures	vii
List of Plates	ix
 CHAPTER 1: INTRODUCTION	 1
1.1 Background	1
1.2 Location and access	1
1.3 Objectives of this study	1
1.4 Methods	3
1.5 Previous Work	3
1.6 History	4
 CHAPTER 2 - REGIONAL GEOLOGY	 7
2.1 Geology of the Hastings Region	7
2.2 Stratigraphy and lithology	7
2.3 Structural geology	10
2.3.1 Folding	10
2.3.2 Faults	11
2.4 Tectonic History	11
2.5 Metamorphism	14
 CHAPTER 3: GEOLOGY OF THE MADOC AREA	 16
3.1 Lithology	16
3.2 Structural geology	19
3.3 Metamorphism	20
3.4 Mineral deposits	20

	Page
CHAPTER 4: GEOLOGY OF THE HENDERSON MINE AREA	21
4.1 Stratigraphy	21
4.2 Lithology	24
4.2.1 Metavolcanics and metasediments of volcanic origin	24
4.2.2 Metapelites	25
4.2.3 Feldspathic porphyry	27
4.2.4 "Phyllite"	29
4.2.5 Tremolitic, micaceous marble (Footwall)	30
4.2.6 Talc horizon	33
4.2.7 Laminated micaceous tremolitic marble (hanging wall)	33
4.2.8 "Mottled-blue" Marble	34
4.2.9 Quartzite with Stromatolitic Texture	37
4.2.10 Moira Lake granite	39
4.2.11 Fracture Fillings of the Henderson Map Area	40
4.2.12 Paleozoic rocks	45
4.2.13 Pleistocene deposits	48
4.3 Structural Geology	48
4.3.1 Folding	48
4.3.2 Faulting	49
4.3.3 Structural control of talc deposits	51
CHAPTER 5: HENDERSON AND RELATED TALC DEPOSITS	53
5.1 Henderson Deposit	53
5.1.1 Morphology and structure	54
5.1.2 Lithology	54
5.1.3 Characteristics of talc product	58
5.2 Conley Deposit	58
5.2.1 Morphology and structure	63
5.2.2 Talc-bearing rocks	63
5.3 East deposit	63
5.3.1 Morphology	64
5.3.2 Talc ore	64
5.4 A brief note on New Conley Deposit	64
CHAPTER 6: GEOCHEMISTRY OF THE ROCKS FROM HENDERSON AND NEW CONLEY DEPOSITS	66
6.1 Description of samples from Henderson and New Conley deposits	66
6.2 Chemical composition of Henderson deposit and its host rock	68
6.3 MgO/CaO ratio	68
6.4 SiO ₂ - CaO - MgO diagram	68
6.5 Chemical zoning across the Henderson deposit*	74
6.6 Chemistry of talc ore and host rock from Henderson deposit versus other talc occurrences in carbonate rocks in North America	74
6.7 Henderson deposit compared with other talc occurrences in carbonate rocks in North America	78
6.8 Summary	80

	Page
CHAPTER 7: FORMATION OF TALC AND TALC DEPOSITS	81
7.1 Background	81
7.1.1 Formation of talc on the seafloor	81
7.1.2 Hydrothermal ("vein forming") activity	82
7.2 Progressive metamorphism of siliceous dolostones	86
7.3 Metamorphism of siliceous magnesite	90
7.4 Retrograde metamorphism	96
7.5 Discussions	97
CHAPTER 8: ORIGIN OF THE HENDERSON TALC DEPOSIT	98
8.1 Critical observations	98
8.2 Applicability of genetic models to Henderson-type talc deposits	102
8.2.1 Relations between 35 criteria and genetic models presented in Chapter 7	104
8.2.2 Precipitation of the talc or talc precursors on the sea-floor	104
8.2.3 Metasomatic (vein forming) activity	105
8.2.4 Prograde metamorphism of siliceous dolostone without magnesite	107
8.2.5 Prograde metamorphism of magnesite bearing siliceous carbonate	109
8.2.6 Retrograde metamorphism	109
8.3 Additional restrictions	110
8.3.1 The time limits on the period of talc formation	110
8.3.2 Conditions that prevailed during the deposition of the talc protolith	112
8.3.3 Closed versus open system	113
8.3.4 Character of fluids and upper temperature limit of the talc formation	114
8.4 Proposed Model	116
8.4.1 Genesis of Henderson deposit	117
REFERENCES	121
APPENDIX I - Field and Laboratory Investigations	127
APPENDIX II - Orientation of the Madoc and Queensborough Synclines	130
APPENDIX III - Descriptions of Thin Sections	133
APPENDIX IV - Detailed Morphology of the Henderson Deposit	141

LIST OF TABLES

	Page
Table 1: Table of Formations for the Grenville Supergroup and Flinton Group in the Hasting region (Moore & Thompson 1980).	9
Table 2: Partial chemical analysis of the light and dark grey phases of the "Mottled blue" marble.	38
Table 3: Chemical analysis of the rocks from Henderson and New Conley deposits.	56
Table 4: Quantitative estimated by SEM/EDXA on the average mill run from Henderson deposit.	59
Table 5: Typical chemical analysis of the average mill run from Henderson deposit.	59
Table 6: Average physical characteristics of the coarse, flaky talc-bearing rock and steatite mixture (mill run) from Henderson deposit.	60
Table 7: Quantitative estimate of mineral compositions by SEM/EDXA on New Conley talc ore.	65
Table 8: Typical chemical analysis of New Conley ore.	65
Table 9: Geochemistry of major rock types (Henderson deposit).	69
Table 10: MgO/CaO ratios of samples from Henderson deposit.	70
Table 11: MgO/CaO ratios of samples from New Conley (341 foot level) drift.	70
Table 12: Chemistry of talc ores from Henderson and Conley deposits.	76
Table 13: Metamorphic reactions in siliceous dolostone.	89
Table 14: Key reactions in the system MgO-SiO ₂ -H ₂ O-CO ₂ system.	93
Table 15: Key reactions in the MgO-SiO ₂ -H ₂ O-CO ₂ system.	94
Table 16: Origin of the Henderson talc deposit.	99
Table 17: Thirty-five criteria in relation with models described in Chapter 7.	103

LIST OF FIGURES

	Page
Figure 1. Location of the talc deposits, Madoc, Ontario.	2
Figure 2. Henderson orebody and neighbouring talc deposits.	5
Figure 3. Tectonic setting of the Hastings region.	8
Figure 4. Metamorphic isograds in Hastings region.	15
Figure 5. Lithology of the Madoc area, simplified map from (Hewitt 1968).	17
Figure 6. Geology of the Henderson mine area. (Back pocket)	
Figure 7. Stratotype section of Henderson mine area.	22
Figure 8. Geology of the Henderson mine (541.65 foot level). (Back pocket)	
Figure 9. Coarse calcite-phlogopite-quartz-sulphide vein cutting fine grained, pyrite-bearing dyke of siliceous appearance.	43
Figure 10. The homogeneity test of deformation in Henderson mine area.	47
Figure 11. Geological map of the decline. (Back pocket)	
Figure 12. Structural control and talc-bearing zones in Henderson mine area.	50
Figure 13. Typical vertical section through Henderson deposit.	55
Figure 14. Conley deposit, underground workings.	61
Figure 15. Typical cross section of the East deposit.	62
Figure 16. Localities of samples submitted for chemical analysis.	67
Figure 17. Linear relationship between MgO and CaO content in selected hand specimens from the Henderson deposit.	71
Figure 18. SiO ₂ -CaO-MgO diagram.	72

	Page
Figure 19. Variation in major elements across the Henderson deposit	75
Figure 20. Henderson deposit compared with other occurrences of talc in carbonate rocks.	77
Figure 21. Solubility relations of magnesian silicates in aqueous solutions.	83
Figure 22. Geology of the Trimouns deposit.	85
Figure 23. Isobaric X_{CO_2} diagram at 5 Kb fluid pressure for reactions in siliceous dolostone.	88
Figure 24. Isobaric equilibrium curves in the system $MgO-SiO_2-H_2O-CO_2$ system.	91
Figure 25. Isobaric equilibrium curves of selected reactions in the low X_{CO_2} range of the $MgO-SiO_2-H_2O-CO_2$ system.	92
Figure 26. Isobaric equilibrium curves of reactions occurring at large X_{CO_2} values in $MgO-SiO_2-H_2O-CO_2$ system.	95
Figure 27. Relative chronology in the Henderson mine area and its relation to Grenvillian orogenic cycle.	111
Figure 28. Logarithmic activity diagrams for the system $CaO-SiO_2-MgO-H_2O$ at 425°C, 0.5 Kb and $a_{H_2O}=1$.	115

LIST OF PLATES

	Page
Plate 1: Inter-metasediments of volcanic origin and metavolcanics	26
Plate 2: Metapelite	26
Plate 3: Laminated "phyllite"	28
Plate 4: Coarse, flaky, white talc-bearing rock	28
Plate 5: Coarse, flaky, white talc-bearing rock	31
Plate 6: Steatite	31
Plate 7: Steatite	32
Plate 8: Laminated micaceous tremolitic marble, hanging wall	32
Plate 9: Quartzite with stromatolitic textures	35
Plate 10: Mottled-blue marble	35

CHAPTER 1: INTRODUCTION

1.1 Background

Talc occurs in a variety of geological environments, but most talc deposits occur either in altered ultramafic and mafic rocks, or in dolomitic marbles.

The Henderson, Conley and East deposits, located near Madoc, in eastern Ontario, belong to the second category. These deposits are unique in Canada because of their large size, chemical and mineralogical uniformity, high talc tenor, association with marble, and stratabound nature. The geology of the Henderson deposit has been subjected to several studies, but because of its complexity, has not been well understood.

1.2 Location and access

The Henderson, Conley and East deposits are located about 1 km southeast of the Village of Madoc, on lots 14 and 15, concession XIV of Huntingdon Township in the Hastings County. The village of Madoc is about halfway between Ottawa and Toronto, at the intersection of highways No. 62 and No. 7 (Fig. 1).

1.3 Objectives of this study

The objectives have been to:

- 1) map the geology of the surface and accessible underground levels;
- 2) Describe the geology of talc deposits and their host rocks;

Fig. 1 - Location of the talc deposits, Madoc, Ontario.

- 3) establish the morphology of the talc deposits;
- 4) determine the mineralogy and chemical composition of the talc deposits and their host rocks;
- 5) determine the structural history of the talc horizon(s) and enclosing rocks;
- 6) establish, to the extent possible, the genesis of the talc deposits.

The results of this work should be useful in delineating extensions of the known talc deposits and in finding new ones.

1.4 Methods

The surface area around the Henderson mine and related deposits was mapped at the scale of 1:1200. Two underground levels in the Henderson mine were mapped at the scale of 1:360. Core from 1981 and 1982 drilling programs was logged. Cross sections of the Henderson and East deposits were produced at the scale of 1:360.

Representative samples of the talc deposit and enclosing rocks were collected and the mineralogy and textural relations examined in thin section. Results, where necessary, were confirmed by X-ray diffraction, and qualitative microprobe analysis. Subsequently ten samples were selected for chemical analysis of the major elements. The detailed field and laboratory methods are described in Appendix I.

1.5 Previous Work

The Henderson deposit and its immediate surroundings have been subjected to numerous geological investigations (Miller and Knight 1913,

Spence 1922, Wilson 1926, Osborne 1931, Sandomirsky 1954, Hewitt 1957 and Roscoe 1966).

Sandomirsky (1954) reviewed the history of the Henderson mine, the production data, and existing hypotheses relating to the formation of the Henderson deposit. He relied in part on geological maps produced by Wilson (1926) and Spence (1922) and concentrated his efforts on the petrography and mineralogy of the Henderson deposit.

Roscoe (1966) mapped a portion of the 541 foot level of the Henderson deposit and concentrated on the structural geology of the talc deposit and enclosing rocks. No known geological work has been carried out on the Henderson or Conley deposit in the last fifteen years.

1.6 History

The discovery of the Henderson talc deposit in Huntingdon Township near Madoc occurred in 1893 (Dickson 1981). It was discovered by Alexander Henderson while ploughing a field. Three years later the first small scale exploitation took place and the operation grew rapidly. The original discovery is now the Henderson orebody (Fig. 2). Production from the Henderson deposit has been continuous since 1896.

The deposit was first mined by open pit and later as an underground mine. It is now being mined at a depth of more than 220 metres. The Conley deposit, an extension of the Henderson deposit was discovered in 1911 (Dickson 1981). It was mined out in 1943. The ownership of Henderson and Conley properties changed hands several times prior to 1937, when both were united under a company known as the Canada Talc Ltd. (Sandomirsky 1954). Canada Talc Ltd. was acquired by Canada Talc

Fig. 2. Henderson orebody and neighbouring talc deposits.

Industries Ltd. in 1951 (Sandomirsky 1954). William R. Barnes Co. Ltd. took control of Canada Talc Industries Ltd. in May 1981.

Canada Talc Industries, based in part on the information obtained in the early part of this study, undertook an extensive diamond drilling program in 1981. The "East" talc deposit was discovered during this drilling program. This deposit is now being prepared for production.

CHAPTER 2 - REGIONAL GEOLOGY

2.1 Geology of the Hastings Region

The talc deposits of the Madoc area are in the Hastings "Basin", (Fig. 3) which forms part of the Central Metasedimentary Belt of the Grenville Province (Wynne-Edwards 1972). The Hastings region is underlain by late Precambrian metavolcanics and metasediments* of the Grenville Supergroup and cut by intrusive mafic to felsic rocks.

2.2 Stratigraphy and lithology

The stratigraphy of the Grenville Supergroup in the Hastings region is complex because of abundant lateral lithological variations (Lumbers 1967, Moore and Thompson 1980). The Grenville Supergroup is subdivided into the Hermon and Mayo Groups (Lumbers 1967, Wynne-Edwards 1972, Moore and Thompson 1972, Moore and Thompson 1980). The stratigraphy of an area northeast of Madoc has been interpreted by Moore and Thompson (1980) as shown in Table 1. A minor unconformity separates the Hermon Group from the Mayo Group. The stratigraphic thickness of the preserved rocks of the Hermon and Mayo Groups was estimated at 8300 metres (Wynne-Edwards 1972).

The Flinton Group overlies the Mayo and Hermon Groups. The base of the Flinton Group is marked by a heterogeneous assemblage of conglomerate and/or black pelitic schist, which are separated from the rest of the Flinton Group by a minor unconformity (Moore and Thompson 1980).

* The numbers that accompany individual lithological descriptions refer to the various units in Table 1.

LEGEND

- Anorthosite, Mangerite, Monzonite
- Proterozoic supracrustal rocks
- Quartzite - feldspathic gneisses
(in Superior province includes
supracrustal greenstone - greywacke belts)
- Tectonic subdivision
- Boundary with younger cover rocks
- Other tectonic boundaries

Fig. 3 - Tectonic setting of the Hastings region (modified from Wynne-Edwards 1972).

TABLE 1. Table of Formations for the Grenville Supergroup and Flinton Group in the Hastings region (Moore and Thompson 1980)

	SW Madoc	Flinton	Fernleigh/Ardoch NE
Flinton Group		(14) Pegmatite intrusive contact	(11) Fernleigh Formation - biotite-carbonate schist
	(13) Stewart Formation - dolomite marble - micaceous graphite- calcite marble	(9) Lessard Formation - biotite-carbonate schist - calcareous quartzo- feldspathic psammite - calc-silicate paragneiss - plutonic pebble conglomerate	(10) Myer Cave Formation - dolomite marble - graphite pelite - carbonate conglomerate, pelite, marble
	(12) Madoc Formation - pelitic schist	(8) Bishop Corners Formation - pelitic schist - quartzite conglomerate - quartzite quartzo-feldspathic psammite - white quartzite conglomerate	
		minor unconformity	
Grenville Supergroup Huron, Mayo Groups		(6) Skootamatta formation - volcanic pebble conglomerate - carbonate pebble conglomerate - calcareous phyllite, psammite	(7) Ore Chimney Formation - garnet-biotite schist
		major unconformity	
		(5) Plutonic rocks 3a hornblende-biotite granodiorite 3b biotite granite	
		intrusive contact	
	(2) Volcanic rocks 2a tholeiite basalt (Tudor fm.) 2b plagioclase-rich basalt, basaltic andesite 2c andesite, andesite breccia 2d dacite, rhyolite		(4) Marble (3) Wacke, tuff
	(1) Mafic, ultramafic intrusive rocks 1a ultramafic rocks 1b Kalar mafic complex		

*Numerical order does not everywhere correspond to stratigraphic order; units are arranged in table so as to show approximate vertical and lateral relations

Abundant lateral lithological changes exist within the Flinton Group (Table 1). These changes are caused by lateral variations in the depositional environment and by variations in the lithology of the older, pre-Flinton source rocks (Moore and Thompson 1980).

Granitoid plutons are known to intrude part of the Grenville Supergroup but predate the Flinton Group (Moore and Thompson 1980, Lumbers 1967, Davidson et al. 1979).

Only late pegmatites penetrate the Flinton Group (Moore and Thompson 1980).

In the southern part of the Hastings region, all the rocks described above are unconformably overlain by Paleozoic arkosic and carbonate rocks. Unconsolidated Pleistocene sediments unconformably overlie both Precambrian and Paleozoic rocks.

2.3 Structural geology

Rocks of the Precambrian age were strongly affected by faulting and polyphase folding, to produce a prominent northeasterly structural grain.

2.3.1 Folding

The folds in the area are characterized by axial plane schistosity (Wynne-Edwards 1972). Parts of the Grenville Supergroup show interference patterns (including large changes in orientation and in plunge of the lineations) caused by interference of at least two major fold sets (Wynne-Edwards 1972).

Three types of folds were recognized in rocks of the Flinton Group by Thompson (1972). They are:

- i. isoclinal folds with variable plunge parallel to regional strike, usually tens of kilometres in length (D_1);
- ii. folds formed by deformation about axial surfaces with northeastern trend (D_2);
- iii. open folds with northwest trending axial surfaces (D_3).

Isoclinal folds are probably responsible for a lithological pattern described by Lumbers (1967) as narrow synclinal marble belts between the anticlinal belts of metavolcanics and non-carbonate metasediments and dome shaped plutonic intrusions.

2.3.2 Faults

Faults of the Madoc-Bancroft region can be subdivided into north to east-northeast faults and west-northwest faults (Lumbers 1967). The style of faulting is not well known; however, at least some of the faults of the west-northwest system are normal (Lumbers 1967), possibly related to the faults of Ottawa-Bonnechere system (Kay 1942, Hewitt 1964). Northwest trending, post-Ordovician faults which control barite-fluorite mineralization in the Madoc area are probably strike slip faults (based on a study of slickensides and striations by Wilson (1929)).

2.4 Tectonic History

The regional tectonic history described below is based on the work of Moore and Thompson (1980). The probable Aphebian crystalline

basement to the Grenville Supergroup comprises complex migmatites and gneisses. These rocks were dated by Krogh and Davis (1968) and Baer (1976) at or more more than 1500 Ma and by Bell and Blenkinsop (1980) at 1430 ± 20 Ma. These dates correspond probably to a metamorphic event (Bell and Blenkinsop 1980).

The consolidation of the basement was followed by the deposition of the Grenville Supergroup, exposed to the northwest of the study area between 1300 and 1225 Ma (Moore and Thompson 1980). The oldest known rocks of the Grenville Supergroup are the mafic (Tudor) volcanics* (2a, Table 1) of the Hermon Group. They have an age of 1286 ± 15 Ma based on Pb-U dating of zircons (Silver and Lumbers 1966)** . This age was confirmed by the Rb-Sr method (Bell and Blenkinsop 1980).

The ages of the intrusive rocks (5, Table 1) of the Hastings Basin were investigated by Silver and Lumbers (1966). They recognized at least two periods of magmatic activity: an early period at about 1266 Ma and a younger period about 1104 Ma. Bell and Blenkinsop (1980) confirmed approximately these dates by determining that a major period of plutonic activity, metamorphism and deformation (Elzevirian orogeny)*** took place between 1250 to 1100 Ma. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios indicate a cogenetic relationship between the earlier magmatic phase and Tudor volcanics (Bell and Blenkinsop 1980).

* Prefix meta is not used in the sections describing regional geology and the geology of the Madoc area to keep in line with references and figures borrowed from the references.

** Recalculated by Bell and Blenkinsop

*** Term proposed by A. Baer for early phase of "Grenvillian orogeny" (Moore and Thompson 1980).

Uplift, erosion and deposition of the Flinton Group was estimated at 1065 ± 25 Ma (Moore and Thompson 1980). The conglomerate at the base of the Flinton Group has a maximum age of 1118 ± 30 Ma obtained by U-Pb method (Davidson et al. 1979). The major period of polyphase deformation and regional metamorphism (Ottawan Orogeny)* took place between 1050 - 1000 Ma.

Two recent models have been proposed for the evolution of the Grenville Province. An aulocogen model was presented by Baer (1976). Subduction followed by continental collision was proposed by Brown et al. (1975). Evidence for each model is summarized as follows (Moore and Thompson 1980): the aulocogen model is based on the limited distribution and thickness of volcanics, supposed "alkalic" character of the volcanics and presence of continuous underlying sialic crust. The model of subduction followed by continental collision is based on the minimum estimated thickness of volcanics of at least 10 km, abundance of tholeiitic and calc-alkalic volcanics and association of the volcanics with the "orogenic" plutons. Moore and Thompson (1980) favour the model of subduction followed by continental collision presented by Brown et al. (1975).

* Term proposed by Moore and Thompson (1980) for the late phase of the "Grenvillian orogeny".

2.5 Metamorphism

Rocks in the Hastings region are not metamorphosed as highly as most rocks in the Grenville Province (Wynne-Edwards 1972). The degree of metamorphism is inversely related to the thickness of the preserved rocks of the Grenville Supergroup (Wynne-Edwards 1972). The lowest degree of metamorphism is attained in Madoc-Millbridge area (Fig. 4) and metamorphic grade increases eastward and westward from the biotite zone "low" (Carmichael, Moore and Skippen 1978).

Fig. 4 - Metamorphic isograds in Hastings region.
(Adapted from Carmichael, Moore and Skippen 1978).

CHAPTER 3: GEOLOGY OF THE MADOC AREA

The Madoc area is located within the Hastings Region. The geology of the Madoc area was mapped at the scale of 1:31 680 by Hewitt (1968). Part of his work is reproduced in order to demonstrate the geographic distribution of the lithological units (Fig. 5). Pleistocene unconsolidated deposits cover about 80% of the area.

The lithological legend of Hewitt (1968) is not entirely equivalent to the stratigraphic interpretation as presented in the section on regional geology by Moore and Thompson (1980), and a simple correlation between the two is therefore impossible.

Geologists from the Ministry of Natural Resources are currently studying the geology of the Madoc area and their work should clarify the stratigraphic relationships. The results of their study were not available at the time of writing.

3.1 Lithology

The salic and mafic volcanic rocks (Fig. 5) were subdivided into Tudor volcanics, Madoc volcanics and Queensborough volcanics (Hewitt 1968). Tudor volcanics extend into Madoc township from the north. They are dark-coloured andesites and basalts. Basalts with green weathering surface are composed mainly of hornblende and plagioclase with minor chlorite and carbonate. Locally they may contain talc and actinolite (Hewitt 1968). The Madoc volcanics outcrop on highway 7, about 3 km west of Madoc and on highway 62 about 2 km north of Madoc (Fig. 5). These black, grey-green or pink volcanics range in composition from

Fig. 5 - Lithology of the Madoc area, simplified map from (Hewitt 1968).
 Pleistocene, unconsolidated deposits ; Paleozoic Black River limestone ; Precambrian rocks: granite ; diorite or gabbro ; pelitic rocks and conglomerate ; marble ; silicated marble ; mafic volcanics ; silic volcanics ; geological boundary ; fault ; fold axis , road .

andesite to rhyolite (Hewitt 1968). Texturally these rocks may be described as massive lavas, pillowed lavas, amygdaloidal lavas, tuffs and agglomerates (Hewitt 1968).

Queensborough salic volcanics outcrop mainly in the Queensborough syncline located 6 km northeast of Madoc (outside of the area covered by Fig. 5), stratigraphically above the Tudor volcanics (Hewitt 1968). They consist of two main types: rhyolite and felsite, and are associated with black pyritiferous slates (Hewitt 1968).

The metasedimentary rocks are comprised of conglomerate, slate, argillite and pelitic schist. Conglomerate bands referred to as "Skootamatta conglomerate" contain pebbles of andesite, rhyolite, dolomite marble, quartzite, quartz, phyllite and plutonic rocks (Moore and Thompson 1980).

Calcitic and dolomitic marble is a thick lithologic unit, varying in colour from white, buff, blue-grey, green to black (Hewitt 1968).

Several granitic plutons occur in the Madoc area. The Elzevir pluton is located about 5 km northwest of Madoc. The Addington pluton is located 15 km southeast to east of Madoc. The Moira pluton is located about 2 km southeast of Madoc. The latter is well exposed on the north shore of Moira Lake (Fig. 5). It is a pink granite composed mainly of albite and quartz with minor microcline (Hewitt 1968).

The Ordovician Black River Formation is composed of reddish, greenish or brown arkose at the base. Chocolate-brown, limestone overlies the basal arkose, and it is overlain by medium grey, medium to thick bedded limestone (Hewitt 1968).

3.2 Structural geology

The Queensborough and Madoc synclines were recognized by Hewitt (1968). The Queensborough syncline, 6 km northeast of Madoc, is outside of the area covered by Figure 5. It is an upright syncline and its plunge was tentatively estimated at 80° towards southwest (Appendix II). The variations in plunge direction of parasitic folds indicate at least two periods of folding. The eastern limb of this syncline is truncated by a northwest-southeast trending fault. The Madoc syncline, north of the village of Madoc (Fig. 5), is overturned to the north, its axial surface trends northeast and its plunge was estimated at 50° towards 116° (Appendix II).

Minor folds are abundant in marbles. Most are cylindrical or slightly conical. Their plunges vary in direction and steepness. These variations are probably due to at least two different periods of deformation.

Two major fault systems have been identified and described in the section concerning regional geology. The faults belonging to these have been reactivated several times (Lumbers 1967). Movements along the faults of the west to northwest system postdate the movement along the east-northeast system (Lumbers 1967). Both Precambrian and Ordovician rocks were affected (Hewitt 1968).

The Moira Lake fault zone (Fig. 5) which acts as a structural control for the fluorite-barite-calcite deposits belongs probably to the west to northwest system. The striations and slickensides indicate horizontal displacement (Hewitt 1968). However, vertical wall rock striations were also observed (Wilson 1929).

The horizontal displacement along one fault of the Moira Lake system was estimated at 100 feet (Wilson 1929). For the majority of the faults, however, the displacement remains unknown.

Minor faults are believed to be abundant in the area (Lumbers 1967). They are best exposed in the underground workings of the Henderson deposit (Hewitt 1968). They are mostly strike-slip faults along which the displacement is impossible to determine, or faults with apparent vertical displacement of less than 2 metres.

3.3 Metamorphism

Precambrian rocks of the Madoc area were subjected to upper greenschist facies metamorphism (Carmichael, Moore and Skippen 1978). The upper limit of garnet-chlorite (greenschist-amphibolite facies boundary), located about 3 km southeast of Madoc trends northeast (Fig. 4).

3.4 Mineral deposits

Madoc is known for its talc and barite-fluorite-calcite deposits. Several other non-metallic deposits and industrially useful rocks currently being mined are nepheline syenite, marble, actinolite and granite. Fluorite, barite, apatite, mica, feldspar, corundum, garnet, andesite, rhyolite and slate have been mined in the past (Lumbers 1967). Mica deposits are being currently investigated.

Iron, gold, lead, arsenic and pyrite deposits were also exploited in the past. A detailed account of these mineral occurrences is given by Hewitt (1964).

CHAPTER 4: GEOLOGY OF THE HENDERSON MINE AREA

The surface area around the Henderson mine and related deposits was mapped in detail (Fig. 6, in the back-pocket). More than 80% of the area is covered by overburden and the outcrops are irregularly distributed.

4.1 Stratigraphy

The sedimentary rocks of the Grenville Supergroup in the Henderson Mine area probably belong to the Mayo Group (Moore 1983, personal communication). The lack of stratigraphic polarity indicators makes it impossible to positively identify top and bottom of the stratotype section (Fig. 7). The stratigraphic relationship of the Mayo Group, in which sedimentary rocks overlie the metavolcanics (Table 1) was applied in construction of stratotype section (Fig. 7).

The thicknesses of various lithologic units cannot be referred to as stratigraphic thicknesses because of the extensive folding. The mafic to intermediate laminated metavolcanics and sediments of volcanic origin are the oldest rocks in the mine area. Their contact with the Moira Lake granite is discordant. Their thickness in the map area cannot be determined, because the contact between metavolcanics and overlying metapelite is not exposed. Metapelite, which contains near its top chlorite-rich horizon and a feldspathic porphyry sill, does not outcrop.

Laminated tremolitic micaceous marble overlies the porphyry sill and/or metapelite. Its thickness is estimated at less than 30 metres. Talc bearing "phyllite" more than 4 metres thick is contained within laminated tremolitic micaceous carbonate. Tremolitic, micaceous dolomitic marble overlies the talc bearing "phyllite" and hosts the main talc horizon (Fig. 7). Tremolitic, micaceous marble forming the footwall of the main talc-bearing zone is over 15 metres thick and that forming the hanging wall is about 3 metres thick. The main talc bearing horizon varies in thickness from 10 metres to 15 metres across the Henderson deposit.

A stromatolitic quartzite overlies the tremolitic micaceous marble. It is about 10 metres thick north of the Henderson deposit (Fig. 7). A "mottled blue" marble overlies stromatolitic quartzite. Its thickness averages from 3 to 5 metres depending on deformation. Stromatolitic quartzite, black talc bearing "phyllite", tremolitic micaceous marble and "mottled blue" marble are useful marker horizons. A thick metadolomitic sequence overlying the "mottled blue" marble does not contain any good markers except two siliceous beds (1.5 metres thick).

The Moira granite* outcrops in the southern portion of the mapped area (Fig. 6 in the back-pocket). The contact between Moira Lake granitoid and metavolcanics and/or metasediments of volcanic origin is discordant. The amphibolite outcrops on the shore of Moira Lake are believed to be older than the Moira granite (Bain 1960).

* Moira granite was also metamorphosed but prefix "meta" is not used.

Late amphibolite (5 to 300 cm thick) dykes cut all the rock units present except the Paleozoic rock and Pleistocene unconsolidated deposits. Several tourmaline bearing dykes occur in the area. They are believed to be related to the Moira Lake complex intrusion (Bain 1960). The age relationship between amphibolite and tourmaline dykes is not clear. However, coarse calcite-quartz veins are younger than amphibolites.

Paleozoic rocks form discontinuous, flat lying sheets unconformably covering all the units previously described. Some of the dykes may be post-Paleozoic, however, it is not likely. All the barite and fluorite veins of the Madoc area are of post-Paleozoic ages. Paleozoic rocks outcrop very rarely. Pleistocene unconsolidated deposits overlie unconformably all the units previously described.

The metavolcanics and metasediments of volcanic origin are cut by dark gray to black fine-grained dykes and some quartz-black tourmaline dykes. Except in the immediate vicinity of granite outcrops they are less deformed than the carbonates.

4.2 Lithology

The descriptions of the rocks of the Henderson mine area (Fig. 6) are based on macroscopic and microscopic observations*. Individual lithologic units are described in stratigraphic order (Fig. 7).

4.2.1 Metavolcanics and metasediments of volcanic origin

They were described as amphibolite by Hewitt (1968). Outcrops of this unit are abundant north of Moira Lake (Fig. 6). Their thickness

* For detailed description of the thin sections, see Appendix III.

cannot be evaluated since the contacts with the Moira granitoid are discordant and the position of the contact with overlying metapelites is unknown. The metavolcanics follow a trend sub-parallel to the carbonates (strike N 45° E, dip 80° NW). They are banded medium to dark green and light pink to gray, or massive and green. Individual bands are 0.5 to 1.5 cm thick (Plate 1) and can be traced for several metres.

Laminated rocks were probably deposited in volcano-sedimentary environment. A light pink to gray component of these rocks is comprised mainly of aphanitic carbonates (mostly calcite). Dark and medium green portions consist of a very fine-grained to aphanitic mass comprised of actinolite chlorite, biotite, hematite and feldspar. Locally these rocks contain disseminated sulphides and pods of sulphides up to 10 cm across. Some very dark and thick beds (up to 2 m thick) observed within banded rocks may be massive flows.

4.2.2 Metapelites

Metapelites do not outcrop in the map area. Information about them was obtained from Bain (1960) and from diamond drill core which cut the East deposit and intersected the upper contact of the metapelites.

Metapelites from the diamond drill core are dark brown, fine-grained with schistose texture. They are composed of brown layers surrounding lenses of light gray or beige colour. The lenses are usually less than 0.5 cm thick and less than 5 cm long.

The rock is composed mainly of quartz, calcite and phlogopite with accessory pyrite, zircon, tourmaline, sphene and apatite. Quartz occurs as anhedral crystals (<0.5 mm) concentrated in bands (Plate 2).

Plate 1. Interlaminated metavolcanics and metasediments.

Plate 2. Photograph of metapelite in plane light. Calcite (ca) is stained red, phlogopite (pl) is light brown and quartz (qz) remains white, opaque is pyrite.

Calcite occurs in anhedral grains less than 1.5 mm across averaging 0.7 mm.

Phlogopite flakes are mostly smaller than 1 mm and are concentrated in parallel planes giving the rock its characteristic laminated appearance.

Pyrite is a common accessory mineral. It occurs as euhedral to subhedral crystals (cubes), which are most abundant in phlogopite bands. Some of the pyrite crystals contain phlogopite and quartz inclusions. Pyrite may make up locally more than 10% by volume of the rock.

Sphene is distributed through the rock as small euhedral grains of reddish colour. Very fine zircon grains create radiation halos in phlogopite flakes. Apatite and tourmaline are very rare accessories.

4.2.3 Feldspathic porphyry

Feldspathic porphyry is not exposed in the Henderson mine area. The only information we have about it is from diamond drill cores which cut the East deposit. It occurs as layers (or lenses), less than 1.5 m thick. It overlies or is intercalated with metapelite. It is light brown or light gray, aphanitic, hard and brittle. In hand specimen it resembles the rhyolite.

However, the rock is composed mainly of plagioclase (88%), which occurs as a fine ground mass (<0.2 mm) and euhedral or subhedral phenocrysts (<1 mm across) which form about 15% of the plagioclase crystals. Amphibole (7% of the rock) occurs as radiating (prisms <1 mm) and is disseminated in the fine plagioclase ground mass. Coarsest

Plate 3. Laminated phyllite. Calcite (ca) is stained, talc (ta), tremolite (tr).

Plate 4. Coarse, flaky, white talc-bearing rock.

amphibole grains are associated with hairline fractures filled by calcite and chlorite. Calcite is anhedral (<0.5 mm), and forms about 1% of the rock mass. Chlorite (<2%) occurs in fractures or as alteration of certain amphibole grains. Subhedral opaque grains (<2%) are disseminated in fine-grained plagioclase matrix.

4.2.4 "Phyllite"

This unit is best observed underground on the third level (Fig. 8), but it was also reported on the seventh level of the Henderson mine (D. Ogden and D. Cook 1981, personal communication). The seventh level of the Henderson deposit could not be systematically mapped because of the dangerous conditions in the mine. "Phyllite" also outcrops at the surface (Fig. 6). It can be used as a marker horizon.

The rock has a charcoal black colour but locally it appears lead gray (especially on the weathered surface). It is characterized by phyllitic sheen. It occurs either as a laminated or massive variety.

a) Laminated variety of "phyllite"

Laminated phyllite is comprised of actinolite, calcite and chlorite or from calcite and talc. Actinolite occurs as randomly oriented prisms and needles 1 mm in length. It is strongly altered and replaced by talc and calcite (Plate 3). Calcite replaces actinolite but it also occurs as bands in association with chlorite or talc. Chlorite is slightly pleochroic and it occurs in form of irregular, deformed flakes. Some chlorite grains are 0.5 mm across but most flakes are smaller than 0.2 mm.

b) Massive variety of "phyllite"

Massive variety is composed mainly of actinolite, talc and dolomite. Actinolite occurs as fine blades and prisms (0.5 mm) averaging about 0.2 mm in length. It makes up to 50% of the rock.

Dolomite is present only as fine remnants (<0.2 mm) within the talc mass (5% volume). Talc appears as fine cloudy alteration covering actinolite blades and prisms. The presence was confirmed by X-ray diffraction. Opaque minerals (sulphides) are irregularly distributed through both massive and banded variety of "phyllite". They are mostly in form of euhedral crystals (<2 mm) or more rarely streaks.

4.2.5 Tremolitic, micaceous marble (Footwall)

It conformably overlies the "phyllite" and forms the footwall of the talc deposits (Fig. 7). It is composed essentially of calcite (30%), mica (38%), tremolite (15%), serpentine (10%) and talc (5%). All the accessory minerals present (opaques, tourmaline and sphene) make less than 2% of the rock by volume. Tourmaline is often concentrated in concordant bands. Calcite, mica, and quartz are observed in contact with each other. Calcite occurs as anhedral crystals (<2 mm) with well-developed cleavage. Twinning is not abundant. Strongly altered calcite crystals are elongated subparallel to the mica flakes (<2 mm). Tremolite occurs as prismatic crystals which locally reach 1 cm in size but in general it is less than 0.7 mm in length.

Talc occurs as cloudy alteration on tremolite. Non-identified opaque minerals (<0.5 mm) occur as anhedral grains. Sphene is present in the form of reddish euhedral crystals (<0.4 mm). Tourmaline is red

Plate 5. Coarse, flaky, white talc-bearing rock. Monomineralic zone composed of talc.

Plate 6. Steatite (unusually rich in opaques). White bands consist predominantly talc, dolomite and tremolite. Green phase is serpentine (sup). Dark patches are pyrite grains.

Plate 7. Steatite. tr = tremolite needles, do = dolomite. Darker brown mass consists of mixture of talc (tk) and serpentine (sup) (plain light).

Plate 8. Tremolitic, micaceous, dolomitic marble. (pl - phlogopite, sup - serpentine bearing band, do + tr - tremolite and dolomite bearing band, tl - euhedral tourmaline crystals).

and strongly altered. It occurs as subhedral crystals (0.4 mm) if embedded in serpentine or strongly deformed it it is hosted by impure siliceous marble. Tremolitic micaceous marble of the footwall is mineralogically and texturally similar to the tremolitic micaceous marble which forms hanging wall of the talc deposits (Fig. 7). It differs from the latter by higher mica content and by more deformed nature of lenses and bands.

4.2.6 Talc horizon

The talc horizon is hosted by tremolitic micaceous marble. The contacts between the talc horizon and tremolitic micaceous marble may be sharp or gradational. It does not outcrop except in the area of borehole C.T. 82-1 (Fig. 6, back-pocket). Thickness of this talc rich zone varies from a few centimetres (Wilson 1926) to 30 metres. The talc bearing zone consists of two major rock types: coarse flaky talc bearing rock (plates 4 and 5) and an aphanitic to fine-grained talc bearing mass (plates 6 and 7) usually referred to as steatite (Fig. 7). The thickest known segments of the talc horizon are known as the Henderson, Conley and East deposits. In this paper they are referred to as Henderson type talc deposits.

Petrologic, mineralogic and geochemical investigations were concentrated on the samples from the Henderson deposit. Detailed rock descriptions and geochemistry are given in the section: "Henderson deposit".

4.2.7 Laminated micaceous tremolitic marble (hanging wall)

It overlies the talc horizon (Fig. 7) and is conspicuous by its

banded appearance, and colour (plate 9). The thickness of bands varies from 2 to 50 mm. Most of the bands have regular and sharp contacts, but in places they are highly irregular and may appear as lenses. The colour of bands varies from white, light green, amber to brown, purplish and medium gray or medium green.

The main mineral components are dolomite (60%), calcite (20%), tremolite (20%), mica (5-15%), talc (5%) and locally serpentine (20%). Sphene, apatite and sulphides are minor components. Dolomite is light gray to light green (when strongly serpentinized dark green) and rarely white. It is usually fine-grained but it may be coarser.

Mica (phlogopite and/or muscovite) occurs in flakes and forms the brown bands. Tremolite occurs usually as prismatic crystals 0.05 cm to 5 cm in length often altering into talc rich fine-grained mass. The coarsest tremolite crystals are present in narrow zones subparallel to the bedding.

In the areas where tremolite crystals are fine (3 mm) and where micas are not abundant purplish quartz bands may be observed.

Individual quartz grains are less than 1.5 mm across. Pyrite is distributed irregularly through the unit in blebs or as cubes usually less than 3 mm across. Dravite forms concordant bands.

Chemical composition of several samples of micaceous tremolitic marble are given in the chapter devoted to geochemistry.

4.2.8 "Mottled-blue" Marble

It displays irregular patches or beds of dark blue-gray and light coloured (greenish, yellowish or grayish white) material. A coarsely

Plate 9. Quartzite with stromatolitic texture. (ca+tr) represents calcite - tremolite zone, quartz (qz) is darker and translucent.

Plate 10. Mottled-blue marble. Calcite is stained red. White material is tremolite-dolomite marble. Dark material is dolomitic marble.

banded (5-50 cm) variety of this carbonate is well exposed in the small quarry about 70 metres north of the Henderson open pit and underground (Figs. 6 and 8 in the back pocket).

The dark gray component of the rock is composed essentially of fine-grained (<2 mm) anhedral dolomite (80%) with fine (<2 mm) prismatic tremolite or actinolite (<15%), phlogopite (<5%). Calcite is present as fracture fillings only. The dark blue gray colour may be due to extremely fine organic inclusions. In several areas, the typical blue gray colour of marble is of substantially lighter tone. These areas correspond usually to zones of strong structural deformation.

The light component of the mottle blue marble is comprised mainly of medium to coarse-grained (2-5 mm) dolomite (80%) and coarse (3-15 mm), tremolite (20%). The coarsest tremolite prisms are found near the centres of light material (no calcite is present in these areas).

Light coloured portions of the mottled blue marble are locally separated from the dark coloured portions by a thin (less than 3 cm thick) white to light gray irregular zone (Plate 10). This irregular zone is rich in calcite. Apparent difference in the chemical analysis of the light and dark component (Table 2) is largely due to different proportions of insoluble tremolite. Tremolite was not digested (Sandomirsky 1954).

Poorly preserved "stromatolitic textures" were also observed in this rock.

4.2.9 Quartzite with Stromatolitic Texture

This rock is best exposed underground on the hanging wall of the Henderson deposit (Fig. 7). Its thickness is variable due to folding, and averages 10 metres. It is white to very light gray or greenish, and finely laminated (Plate 9). The rock consists of quartz (40-70%), talc (5-15%), dolomite, calcite (10-15%), and tremolite (15-20%).

Quartz is granular and cloudy. Individual grains are less than 0.3 mm in size and appear annealed (grain contacts form regular triple junctions with an angle of 120°).

Calcite is distributed in the quartz mass as individual granular grains, less than 0.5 mm in diameter. Where calcite is enclosed by the tremolite-talc mass its grain boundaries are highly irregular and the grains are coarse but never larger than 1.5 mm.

Tremolite occurs as prisms with well-developed transverse fractures. Individual prisms are less than 1.5 mm long. Most of the prisms are smaller than 0.5 mm and occur as radiating aggregates. Tremolite is cloudy, and is commonly altered to talc and calcite. Talc occurs only as a fine alteration of tremolite.

Dolomite is present only as few isolated grains, enclosed in quartz mosaic. Dolomite is granular. It was distinguished from calcite by staining. Calcite with apatite occurs as fine (<0.3 mm) grains at triple junctions formed by quartz or as individual grains in tremolite-talc mass. It makes less than 1% of the rock.

Minerals in contact with each other are: quartz-talc-calcite and quartz-tremolite-talc. Microscopic examination also reveals that the stromatolitic texture is formed by the alignment of fine (0.5-2 mm) lenses of quartz along the horizons parallel to the stratigraphy. The

Table 2. Partial chemical analysis of the light and dark gray phases of the "Mottled blue" marble. (Compiled from Sandomirsky 1954.)

Source	Gray phase		Light phase	
	Sandomirsky 1954	Wilson 1926	Sandomirsky 1954	Wilson 1926
CaO	33.31	31.21	27.27	25.15
MgO	19.30	21.60	13.46	15.70
Insoluble	1.21	0.60	25.24	23.04

individual lenses are composed of a very fine euhedral, granular aggregate and are separated by talc, calcite and tremolite from other lenses.

The origin of the above described stromatolitic texture has been debated by several authors. Logan (1864) believed that these textures were fossils of ancient organic life. He termed these textures *Eozoon canadense*. Later authors (Tarr and Keller 1940) believed that the stromatolitic texture was produced by metamorphism of chert layers.

The most recent investigations (Bourque et al. 1982) support Logan's hypothesis. Stromatolitic textures are not restricted only to this stratigraphic unit. Poorly preserved "stromatolitic" textures were also observed in the adjacent "mottled blue" unit.

4.2.10 Moira Lake granite

The Moira Lake granite is represented in the map area only by outcrops of pink to gray granitoid on the north shore of Moira Lake (Fig. 6). The outcrops of granitoid 80 m southeast of Conley workings were mapped and described as "hybrid phase" of Moira Lake granite (Bain 1960, Hewitt 1968). These outcrops are cream to very light pinkish on the weathered surface and display faint layering (possibly primary sedimentary bedding). Concentration of mafic minerals varies from 5% to 30% by volume.

Orthoclase, plagioclase, quartz, biotite, chlorite, clinozoisite, hematite, pyrite, magnetite and zircon were identified in thin section. Plagioclase (20-60%) is hypidiomorphic and shows polysynthetic and carlsbad twinning. It may form phenocrysts up to 1 cm across and alters to sericite and clinozoisite. Orthoclase (15-35%) occurs as subhedral

crystals (1 cm). Quartz (5-25%) is fractured and it forms grains 5 mm. Green biotite (5-25% of the rock mass) is often altered to chlorite and it contains very fine zircons. Chlorite (7%) is present in form of fracture fillings (in association with hematite) or as alteration product of biotite. Apatite (in trace) occurs as fine inclusions in plagioclase. Zircon (in trace) occurs as inclusions in biotite. The hybrid intrusive phase was explained by Bain (1960) as an introduction of the Moira Lake granite into graywackes.

No radiometric age is available for Moira Lake granite. However, if Moira Lake granite is an apophysis of the Addington pluton which occurs several kilometres east of the mapped area (as claimed by Bain 1960), both intrusions would have similar age. The radiometric Rb/Sr age of the Addington pluton is 1060 ± 30 Ma (Bell and Blenkinsop 1980).

4.2.11 Fracture Fillings of the Henderson Map Area

Several types of fracture fillings were observed on the surface and underground. They may be classified as follows:

- a) dark green to black amphibolite dykes
- b) mica, pyrite and tourmaline-bearing veins
- c) sulphide bearing fine-grained veins of siliceous appearance
- d) calcite-filled cavities and fractures
- e) calcite-phlogopite-quartz-sulphide veins
- f) talc-filled fractures
- g) serpentine-filled fractures
- h) chlorite-filled and hematite-filled fractures

- a) Dark green to black amphibolite dykes are widespread in the mine area. They vary in thickness from 20 centimetres to 10 metres. The amphibolites have variable texture and composition and are locally sheared on their contact with dolomite. Because of their relatively high competence when compared with carbonates they fracture easily. Fractures may be filled with hematite, pyrite, calcite, salmon-pink calcite-quartz veins or other fracture fillings. These dykes have been referred to as "madocite" by all previous workers. "Madocite" has become a loosely used term in the Madoc area. The term was probably introduced by Wilson in 1926 (Sandomirsky 1954). Wilson (1926) reserved this term for fine-grained dark rock consisting of fine, needle-like tourmaline crystals, tremolite, and minor pyrite. Wilson (1926) also noted that "madocite" dykes contained phlogopite near the margins. Later, all mine operators, and engineers called any dark coloured rock in the mine area "madocite". Dark laminated dolostones, amphibolites, mica bearing shear zones, "phyllite" rocks or metavolcanics have been called "madocite" at one time or other.
- Sandomirsky (1954) investigated several "madocite" dykes and concluded that the rock is far more complex in composition than described by Wilson (1926). Plagioclase, quartz, chlorite, pyrite, sphene, apatite, zircon, phlogopite, tourmaline (black and brown) and tremolite were identified in madocite dykes by Sandomirsky (1954).
- b) Mica, pyrite and tourmaline bearing veins and shear zones are as common as amphibolite dykes described in (a). They vary in

thickness from 1 cm to 8 metres. In some cases type (a) and type (b) dykes found in the vicinity of the Henderson deposit may be filling the same fractures. These veins are composed of amber mica flakes (0.5-5.0 mm). Mica comprises between 70 and 90% of the rock by volume. Pyrite occurs as euhedral crystals 0.5 to 3 mm in size and makes 5-15% of the rock. Sphene (<1 mm) and quartz (<0.2 mm) and apatite (<0.3 mm) are accessory minerals.

- c) Sulphide-bearing fine-grained, veins of siliceous appearance are observed on the third level of the Henderson mine and the ramp. These contain a significant amount of sulphides (pyrite and/or arsenopyrite) as fracture fillings or disseminations. These veins vary in size from 3 cm to 5 metres but are not abundant. Some of these veins are fractured in a manner described in (b). No thin section of this aphanitic or fine-grained material was made.
- d) Calcite filling - Several fissures contain perfect, euhedral, smoky-gray calcite crystals 0.5-3 cm in size. These calcite crystals are locally covered by sulphides (marcasite?) smaller than 2 mm. Other fillings or gouge may also be present in these fissures.
- e) Calcite-phlogopite-quartz-sulphide veins were observed underground. The best example of this vein is located in the northern extremity of the decline. Veins are invariably emplaced into brittle rocks (dark green to black amphibolite dykes or siliceous sulphide rich fine grained veins. They usually cut across the older dykes or veins at a right angle (Fig. 9), terminate at dyke (or veins) contact and never extend more than

Fig. 9 - Coarse calcite-phlogopite-quartz-sulphide vein cutting fine-grained, pyrite bearing dyke of siliceous appearance.

44

30 cm into marble. Calcite occurs as irregular masses up to 40 cm across, and constitutes 70-90% of the rock by volume. Mica is light coloured and forms hooks up to 2 cm across. It is not present, in all the veins. Quartz is smoky gray aphanitic. It does not form euhedral crystals, and it makes 10 to 15% of the rock. Sulphides are usually fine-grained (<0.5 cm) and are euhedral. Although both smoky-quartz and salmon-pink calcite are considered as favourable indicators in prospecting for radioactive elements, none of these pegmatites was investigated for the presence of uranium. This is probably because of the very limited dimensions of these veins.

- f) Talc-filled fractures and cleavages in marble are abundant in the vicinity of the Conley No. 3 shaft and in other areas investigated by diamond drilling. They are less than 2 mm thick but talc may make up to 20% of the marble, as it is controlled by fracture concentration.
- g) Serpentine filled fractures were observed only in the diamond drill holes C.T. 82-20 and C.T. 82-21 (Fig. 6). They are dark green usually 1-4 mm thick and have slightly diffused contacts. Marble which host these infillings appears also greenish, and bedding planes are strongly contorted.
- h) Chlorite-filled and hematite-filled hairline fractures occur mostly in the thick undifferentiated marble sequence overlaying "mottled-blue" dolomite.

Age relationship between fracture fillings, dark green to black amphibolite dykes and tourmaline bearing veins, is not well established, but tourmaline bearing veins are probably the oldest.

oldest. They are affected by folding and faulting. Siliceous, pyrite rich fine-grained veins are older than salmon-pink calcite pegmatite.

Serpentinized zones and serpentine-filled fractures are specially related to amphibolite dykes; however, no definite age relationships between the two could have been established.

Chlorite and hematite-filled fractures postdate amphibolite and siliceous sulphide rich fine-grained veins. They are known to form a swarm south of Henderson deposit and are most abundant in near surface conditions. No dykes or fracture filling described above except the hematite chlorite-filled fractures are known to cut Paleozoic rocks.

4.2.12 Paleozoic rocks

Paleozoic rocks of the Black River group unconformably overlie the Precambrian rocks. Percussion surface drilling in the Henderson mine area indicates that the thickness of cover may be locally over 7 m.

The physical appearance of the Paleozoic rocks varies considerably. Two main types are recognized in the mine area based on physical appearance and colour:

- a) purplish to dark brown sandstone
- b) green purplish, flaggy fine-grained silt.
- a) The purplish to dark brown sandstone - It is generally poorly sorted; however, beds display graded bedding. Individual beds vary from 2 cm to 50 cm in thickness. The grains are subrounded to subangular (1 to 3 mm in diameter) composed mainly from quartz and

feldspars. The cement consists of red hematite and some calcite. This rock-type contains subangular to angular fragments are most abundant near the discordant contact with underlying rocks of the Grenville Supergroup.

- b) The green-purplish, flaggy silt - It may be deposited directly on the Precambrian rocks or on the purplish to dark brown Paleozoic sandstone. Macroscopic examination indicates that this rock is composed mainly of feldspars, quartz and chlorite. The grains are less than 2 mm in diameter and subangular. The green coloured portion of the rock is predominant and encloses purplish, hematite stained lenses usually less than 10 cm in length and 3 cm in width. The purplish lenses are finer grained and appear more siliceous. Paleozoic rocks described above belong to the basal member of the Black River Group (Hewitt 1968). No typical chocolate brown, Black River limestone was encountered in the mine area. Rapid examination of the borehole C.T. 82-14 drilled to test for weathering effects on the talc zone in the area of the East deposit revealed several detrital tourmalines embedded in the bottom portion of the purplish brown Paleozoic rock. These dravite crystals had the same size and appearance as those in the underlying rocks of the Grenville Supergroup. Systematic microscopic examination of Paleozoic rocks overlying the talc deposits may reveal the presence of the detrital talc.

Fig. 10 - Homogeneity test. Poles of layering from the Henderson Mine area. Dark dots represent probable orientation of the fold axis. These orientations are in agreement with orientations of fold axes, observed underground and measured by Roscoe (1966).

* number of measures, ** contours in %

A - Henderson deposit (3rd level and decline)

B - New Conley deposit (3rd level)

C - Surface covered by Figure 6

D - Localities A, B and C combined

4.2.13 Pleistocene deposits

Pleistocene unconsolidated deposits cover most of the lowland in the mine area. They consist of boulder and kame moraine (Hewitt 1968) and were studied in the mine area by Sandomirsky (1954). The orientation of glacial fluting and glacial striae varies from $N25^{\circ}E$ to $N30^{\circ}E$ (Sandomirsky 1954).

4.3 Structural Geology

The structural geology in the Henderson mine area is complex due in part to multiple-phase deformation. Small outcrop area, poor outcrop distribution and ductile rocks make structural interpretation difficult. The general trend of bedding in mine area is 042° and dip is about $85^{\circ}S$.

4.3.1 Folding

Three phases of ductile deformation were identified in the Madoc area by Thompson (1972). He recognized first phase (D_1) isoclinal folding, second phase (D_2) deformation about axial surfaces with northeast orientation and third phase (D_3) open folds with northwest oriented axial surfaces (Moore and Thompson 1980). The folds reported from Henderson underground excavations are steeply plunging towards NW and strike of their axial fold planes was estimated at $N60^{\circ}W$ (Roscoe 1966).

The poles of layering from the third (541 foot) level of Henderson deposit (Fig. 10a), 3rd level of New Conley deposit (Fig. 10b) and from the surface (Fig. 10c) are distributed along the great circles. Figures 10a, 10b, and 10c are combined in Fig. 10d. The orientation of the fold

axes from these figures supports observations of Roscoe (1966). The folds described by Roscoe (1966) are probably related to third phase (D_3) deformation described by Moore and Thompson (1980). The folds related to D_2 and D_1 deformations were established by tracing selected lithological markers and from the orientation of the layering in marbles.

4.3.2 Faulting

(Wilson (1926), Hewitt 1957), Sandomirsky (1954) and Roscoe (1966) refer to major faults in the presently inaccessible portion of the underground workings. Hewitt (1968, p. 17) states:

"There is a considerable amount of faulting, although the fault pattern has not been worked out. Wilson (1926) notes that, on the fourth level of the Henderson mine, the talc orebody is cut by an overthrust fault about 50 feet west of the No. 2 shaft. This fault strikes roughly east-west and dips about 45° to 50° north. On the fourth level, there is an apparent horizontal displacement of about 50 feet. This displacement is reported to fade out toward the surface into an open fold. This fault zone also appears on the fifth and sixth levels of the Henderson mine. What may be a subsidiary fault, striking somewhat south of west and dipping vertically, can be seen just north of the ore zone on the seventh level of the Henderson mine. Zones of faulting are also seen in the Henderson Conley crosscut and in the Conley workings at No. 3 shaft, but no data on these faults are available."

No major measurable displacement (over 10 m) was observed in the accessible workings. Several minor faults with apparent vertical displacement of less than 2 m cut the beds of host rock near the Henderson deposit (most of them show less than 1 m apparent displacement). Important fractures, some of which may be traced up to 40 metres were observed underground. One of these major fractures is exposed on the ramp and twice on the 541.65 foot level of New Conley deposit (Fig. 11 in pocket). This fracture is parallel to the bedding.

Fig. 12 - Structural controls and talc zones in the Henderson Mine area;
a model favoured by Roscoe (1966).

It is filled by smoky euhedral calcite crystals covered by marcasite. Horizontal and vertical lineations are observed in soft gouge along this fracture; however, the sense of the movement is impossible to determine.

Drill logs from Canada Talc's archives indicate presence of the waterfilled fracture zone in the footwall of the Henderson deposits. This fracture zone is confirmed by an old borehole drilled horizontally from the 541 level which leaks water under considerable pressure and could not be sealed. Borehole C.T. 82-4 (Fig. 6) intersects a strongly altered zone (near the surface) which may be part of the waterfilled, underground zone. This altered, water bearing zone may be in fact a fault (Fig. 12) of unknown displacement postulated by Roscoe (1966), and shown by Bain (1960), or it may be a surface of detachment produced during folding.

4.3.3 Structural control of talc deposits

The northwestern extensions of the Henderson talc deposit are Conley and East deposits. The stratigraphic control in the area of East deposit was established by drilling and core logging. Individual talc deposits are probably separated by steeply plunging folds which may grade into faults (Fig. 6).

The southeastern extremity of the Henderson deposit was believed to correspond to the nose of major fold (Wilson 1926, Sandomirsky 1954, Roscoe 1966); however, no satisfactory interpretation (in form of map) was previously published. This is probably because early workers did not recognize effects of multiple phase deformation.

The most satisfactory interpretation based on the information collected by the author up to March 1982 involves multiple-phase folding and faulting (Fig. 6)*. Additional drilling or trenching would be necessary to confirm the validity of the structural information presented in Figure 6.

Detailed mapping of the new open cast excavation of the East deposit may shed more light on the type of folding or faulting separating the East deposit from the Conley deposit.

Detailed geological mapping of the underground excavations of the New Conley deposit is necessary to establish if talc deposits in the vicinity of No. 3 shaft are related to the main talc horizon.

* Isoclinal fold (fig. 6) has major stratigraphic implication. Isoclinal folds of the Madoc area occur in pre-Flinton rocks only (Moore 1984, personal communication).

CHAPTER 5: HENDERSON AND RELATED TALC DEPOSITS

Talc occurs in several geological environments in the map area (Fig. 6). These occurrences may be subdivided into Henderson type deposits (Henderson, Conley and East deposits), New Conley deposit and other talc occurrences. Only the Henderson type deposits are described in detail.

Henderson type deposits were and still are economically the most important. Their history was summarized in the introduction. Henderson type deposits are sheet or lens-like bodies corresponding to the widest known sections of the main talc horizon (Fig. 6). None of these deposits outcrop in the area. The extent of the Main talc horizon is known from isolated outcrops, underground workings, and 1981-1982 diamond drilling (see boreholes CT-81-3, CT-81-4, CT-81-7, CT-81-9, CT-81-10 and CT-82-1, CT-82-4, CT-82-5, CT-82-8 of Fig. 6). The talc horizon is interrupted and displaced by folding and/or faulting, complicating interpretation and exploration. The thickness of the talc varies from a few centimetres to over 30 m.

5.1 Henderson Deposit

The Henderson deposit did not originally outcrop, but at present it is exposed by extensive overburden stripping. Open pit and underground workings of the Henderson deposit are no longer accessible except for a portion of the 541 foot level and decline which are connected to No. 3 shaft (Fig. 2).

5.1.1 Morphology and structure

The Henderson deposit is a tabular sheet. It is over 250 m long, 7 to 25 m thick, at least 250 m deep and open at depth (Fig. 13). It strikes N42E and dips 65° to 85°NW. The strike changes abruptly to the northwest at the western extremity of the deposit where it may be terminated by a fold and/or fault (Fig. 6).

The eastern extremity of the Henderson deposit is probably separated from the Conley deposit by a steeply plunging fold grading to a fault (Fig. 6). Several amphibolite dykes and mica, sulphide and tourmaline veins cut the deposit. However, no direct talc-dyke relationship is observed. Near the surface the deposit is truncated by an unconformity and covered by Paleozoic rocks and unconsolidated Pleistocene deposits. Detailed morphology of the deposit is given in the Appendix IV.

5.1.2 Lithology

Talc rich rocks of the Henderson deposit may be subdivided into two major types:

- 1) coarse, flaky, talc bearing rock
- 2) steatite (massive, aphanitic to fine grained, talc bearing rock)*.

Coarse, flaky talc-bearing rock is characterized by snow-white to light green flakes (from 0.5 to 2 cm across) of talc. No banding, laminations or other remnant sedimentary textures could be observed macroscopically or microscopically, except for a few concordant.

* These rocks are excellent talc ores (coarse flaky talc-bearing rock is the highest grade ore).

Fig. 13 - Typical vertical section through Henderson deposit (for location see Appendix IV).

1. Phyllite
2. Tremolitic micaceous dolomitic marble
3. "Lean" steatite
4. Coarse, flaky talc rock and steatite
5. Tremolitic, micaceous marble
6. Quartzite with stromatolitic texture
7. "Mottled-blue" dolomite
8. Undifferentiated dolomite

TABLE 3. Chemical analyses* of the rocks from Henderson and New Conley deposits

Deposit	Henderson.												New Conley	
Sample No.	R-81-52	R-81-110	R-81-110A	R-81-112	R-81-116A	R-81-120	R-81-121	R-81-129	R-81-133	R-81-139	CON-82-2	CON-92-3		
Element	%	%	%	%	%	%	%	%	%	%	%	%		
SiO ₂	56.5	47.8	53.8	52.2	53.4	48.3	56.0	56.5	43.4	27.6	26.2	13.2		
Al ₂ O ₃	1.55	0.75	0.10	6.55	0.25	2.70	2.00	1.60	0.70	7.15	1.05	0.95		
MgO	26.5	28.4	30.2	9.66	30.3	22.6	26.7	25.1	32.1	18.5	26.9	24.3		
CaO	9.45	9.00	4.50	13.1	4.49	14.2	8.94	10.3	8.07	19.2	19.6	24.4		
Na ₂ O	0.46	0.14	0.08	0.63	0.08	1.18	0.44	1.02	0.19	0.26	0.07	0.08		
K ₂ O	1.41	0.53	0.04	4.57	0.17	2.28	1.69	1.64	0.47	6.10	0.11	0.50		
TiO ₂	0.10	0.10	0.10	0.40	0.10	0.22	0.13	0.19	0.10	0.63	0.10	0.12		
P ₂ O ₅	0.02	0.001	0.01	0.02	0.01	0.03	0.01	0.01	0.01	0.02	0.03	0.04		
MnO	0.03	0.03	0.02	0.03	0.01	0.05	0.02	0.04	0.05	0.03	0.03	0.03		
S	0.41	0.08	0.05	1.61	0.0	0.81	0.01	0.01	0.04	2.08	0.03	0.07		
Fe ₂ O ₃	0.83	0.33	0.13	1.83	0.21	1.76	0.33	0.73	0.43	3.09	0.57	0.44		
L.O.I.	3.67	13.1	10.7	9.60	10.8	7.00	3.34	2.82	13.4	16.9	25.4	36.0		
Rock Type**	2	4	3	1	3	1	2	1	2	5	6	6		

* The methods of analysis are described in Appendix I.

** Lithological types: 1 - tremolitic micaceous marble; 2 - steatite; 3 - coarse, flaky talc;
 4 - transition zone between coarse, flaky talc and tremolitic micaceous marble; 5 - tremolitic micaceous marble from a shear zone; 6 - very fine-grain marble from New Conley deposit.

tourmaline bearing layers or siliceous layers which are of uncertain origin.

The coarse, flaky talc bearing rock is comprised of talc (90%), dolomite (<5%), calcite (<1%), tremolite (<5%), serpentine (<2%) and mica (<2%) (samples R-81-110A and R-81-116A, Appendix III). Undeformed crystals of dravite form local concordant bands.

Dolomite coated by talc, corroded islands of dolomite and tremolite enclosed in talc mass and pseudomorphs of talc after tremolite suggest that the coarse, flaky talc-bearing rock was formed by replacement of tremolite and carbonate (dolomite and possibly magnesite) by talc. Dolomite + talc and tremolite + talc are observed in contact with each other.

Calcite is not present in the higher grade ore but may be observed in marginal materials. Chemical analyses of the R-81-110A and R-81-116A indicates that MgO, SiO₂ and CaO are the most abundant major oxides (Table 3). Geochemical data will be treated in detail in the following chapter.

Steatite is light green, gray, light brown or white. It is hard, compact, aphanitic to fine-grained material, which breaks along conchoidal fractures and cleavages. It may contain very distinct light gray, white, light green, dark green or brown laminations and bands. The green colour is related to the presence of serpentine. Some of the gray colour variations are concentrations of opaque minerals (Plate 9). Individual laminations may be traced up to 10 metres and are highly contorted. These laminations may be primary sedimentary features, because they are parallel to bedding and even cross bedding was found in a block of this material.

Steatite is comprised of talc, dolomite, tremolite, serpentine with or without calcite, sulphides and mica in various proportions (samples R-81-116B, R-81-116C, R-81-116D, R-81-121, R-81-133, see Appendix III). Minerals in contact with each other are: talc-dolomite, talc-dolomite-serpentine, tremolite-talc and possibly talc-tremolite-quartz. The chemical composition of samples (R-81-52, R-81-121 and R-81-133) are given in Table 3.

The two types of talc bearing rocks (coarse, flaky talc and steatite) grade into each other over a distance of less than 1 metre. The proportion of these two types of rock in the Henderson deposit is about 1:1 (Roscoe 1966). Although usually surrounded by steatite, the coarse, flaky talc rocks may grade directly into tremolitic micaceous marble. Steatite may contain zones of only partly steatized dolomite.

5.1.3 Characteristics of talc product

Mineralogical, chemical and physical properties of the average mill run (product) differ from those of coarse, flaky ore. Samples of mill run include not only coarse, flaky talc but also steatite and some host rock (tremolitic micaceous marble), which may contain sulphides. Typical mineralogical, chemical and physical properties of mined and milled materials are given in Tables 4, 5 and 6.

5.2 Conley Deposit

The Conley deposit is located on strike northeast of the Henderson deposit (Fig. 2). It does not outcrop and underground workings are no longer accessible. It was never subject to systematic geological mapping.

TABLE 4. Quantitative estimates by SEM*/EDXA** on the average mill run from Henderson deposit (Goldberg and Wehrung 1981).

Dolomite	24.0%
Talc	71.4
Tremolite (prismatic)	0.2
Antigorite	2.6
Phlogopite	1.8
	<hr/>
	100.0%
Estimate obtained by weight difference after digestion	

* Scanning electron microscopy

** Energy dispersive X-ray analysis

TABLE 5. Typical chemical analysis of the average mill run from Henderson deposit (Richardson 1981).

MgO	25-28%
SiO ₂	42-45
CaO	9-12
Al ₂ O ₃	2-3
Fe ₂ O ₃	.5-1
LOI	10-12
Water Soluble Iron	nil

TABLE 6. Average physical characteristics of the coarse, flaky talc-bearing rock and steatite mixture (mill run) from Henderson deposit (compiled from Ogden 1981).

Form of the Particles	Platy
Colour	Pure white
Brightness of dry ore (green filter) at 30 mesh	94-95
Brightness of dry ore (green filter) at -325 mesh	95-96
Acid soluble content in the central zone of the orebody	25-30% (in form of unusually white dolomite).

Fig. 14 - Underground excavations, Conley deposit (compiled from files of Canada Talc Industries Ltd.).

Fig. 15 - Typical cross section of the East deposit.

5.2.1 Morphology and structure

The underground workings are outlined in Figure 14. The drifts were excavated in talc (Evans 1926) and their outline at various levels is an excellent indicator of the strike and dip of the deposit. Dip varies between 75° and 85° N. The strike of the deposit is about N45E. The deposit is about 125 m long and at least 3 m thick. It is keel-shaped (length decreases with depth). It was cut by several dark dykes (Evans 1926).

5.2.2 Talc-bearing rocks

The talc-bearing rock of the Conley deposit is very similar to the talc-bearing rock from the Henderson deposit but of better quality (Sandomirsky 1954). Chemical analysis confirms that the talc ore from Conley deposit is similar to the talc ore from the Henderson deposit. (The difference in CaO content will be discussed under the topic of geochemistry, Table 10.)

5.3 East deposit

The East deposit is located 100 m from the Henderson deposit (Fig. 2). It is similar to the Henderson deposit in every respect. It does not outcrop but it was thoroughly investigated by diamond drilling (Fig. 6).

The stratigraphic sequence ("phyllite", banded tremolitic micaceous marble, talc horizon, presence of the tourmaline layers, etc.) suggests that it belongs to the same horizon as Henderson deposit.

5.3.1 Morphology

The deposit is at least 120 m long and its thickness varies from 5 m to 30 m. Typical cross section of the deposit is shown by Figure 15.

5.3.2 Talc ore

The ore consists of coarse, flaky talc-bearing rock and steatite and includes also limited quantities of tremolitic micaceous marble. Coarse, flaky ore consists mainly of talc with some dolomite, tremolite, calcite, phlogopite, minor vermiculite, chlorite and quartz (Blount 1982).

5.4 A brief note about New Conley Deposit

The New Conley talc deposit is located near Conley No. 3 shaft (Fig. 2). The morphology of the deposit is poorly known. The ore is a brittle, fractured white to light green dolomite marble, where talc occurs as fracture fillings less than 3 mm thick. Dolomite, tremolite and talc are major mineral phases, phlogopite and antigorite are minor mineral phases (Table 7). Calcite was identified by staining.

A partial chemical analysis of the New Conley ore, supplied by Canada Talc Industries is shown in Table 8 (no other chemical analyses are known).

TABLE 7. Quantitative estimate of mineral composition by SEM/EDXA on New Conley talc ore (Goldberg and Wehrung, 1981)

Dolomite* +	67.0%
Talc	10.1
Tremolite	10.6
Antigorite	1.5
Phlogopite	7.3
Unidentified	<u>3.5</u>
	100.0%

* Estimate obtained by weight difference after digestion (Goldberg and Wehrung, 1981).

+ Calcite was identified by staining of thin sections by the author, although it is shown to be absent.

TABLE 8. Typical chemical analysis of New Conley Ore (Dolfill & Talfill Products*).

Major Oxide	% Range
MgO	20 - 24
SiO ₂	16 - 18
CaO	26 - 30
Al ₂ O ₃	0.5 - 1
Fe ₂ O ₃	0.5 - 1
LOI	30 - 35

* Commercial names

CHAPTER 6: GEOCHEMISTRY OF THE ROCKS FROM HENDERSON AND NEW CONLEY DEPOSITS

6.1 Description of samples from Henderson and New Conley deposits

Ten samples from the Henderson deposit and two samples from the New Conley deposit were analyzed for major elements (Table 3). The samples are briefly described below (see Appendix III for detailed descriptions). The methods of analysis are described in the Appendix I. Sample localities are shown in Figure 16.

a) Lithology of samples from Henderson deposit

Samples R-81-110A and R-81-116A represent coarse, white and flaky talc. Samples R-81-52, R-81-121 and R-81-133 correspond to steatite. Samples R-81-120, R-81-129 represent typical tremolitic, micaceous marble. Sample R-81-112 is a coarse tremolitic marble that appears unaltered and contains an above average amount of quartz as laminations. Sample R-81-139 is also tremolitic micaceous dolomite but it was located in a shear zone. It contains more calcite and amber mica than the typical tremolitic, micaceous talc-bearing marble.

b) Lithology of samples from New Conley deposit

Fine-grained marbles (samples CON-82-2 and CON-82-3) are macroscopically and texturally similar to steatite from the Henderson deposit. However, their chemical composition is characterized by lower SiO_2 and higher MgO and CaO concentrations (Table 3).

Fig. 16 - Localities of samples submitted for chemical analysis.

6.2 Chemical composition of Henderson deposit and its host rock

Composition of the main talc-bearing rock types and adjacent tremolitic micaceous marble from the Henderson deposit are summarized in Table 9.

6.3 MgO/CaO ratio

The MgO/CaO ratios in coarse talc-bearing rocks and steatite are higher than in average tremolitic micaceous marble (Table 10). Although some specimens (CON-82-2, CON-82-3) from the New Conley have textures identical to steatite, their MgO/CaO ratios are lower (Table 11). Most of the MgO/CaO ratios from the Henderson deposit (Table 10) are higher than that of a theoretical dolomite. High MgO/CaO ratios suggest that, if the talc deposit was formed in a chemically closed system, then an appreciable amount of magnesite was required within the dolomite rock. On the other hand if the system was chemically open during the talc forming process and original rock was siliceous dolomite, then either MgO may have been added to the system, CaO may have been leached from the system, or addition of MgO and leaching out of CaO may have taken place.

An inverse, linear relationship exists between MgO increase and CaO decrease in all the samples of the Henderson deposit except sample R-81-139, which corresponds to a thin shear zone (Fig. 17).

6.4 SiO₂ - CaO - MgO diagram

SiO₂, MgO and CaO are the most abundant components of the talc-bearing rocks of the Henderson deposit (Table 3). An SiO₂-MgO-CaO diagram (Fig. 18) is the most convenient plot to compare the chemistry

TABLE 9. Geochemistry of major rock types*

Rock Type	Sample No.	SiO ₂	Al ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	MnO	S	Fe total as Fe ₂ O ₃ L.O.I.
tremolitic micaceous marble	R-81-112	52.2	6.55	9.66	13.1	0.63	4.57	0.40	0.02	0.03	1.61	1.83
	R-81-120	48.3	2.70	22.6	14.2	1.18	2.28	0.22	0.03	0.05	0.81	1.76
	R-81-129	56.5	1.60	25.1	10.3	1.02	1.64	0.19	0.01	0.04	0.01	0.73
steatite	R-81-52	56.5	1.55	26.5	9.45	0.46	1.41	0.10	0.02	0.03	0.41	0.83
	R-81-121	56.0	2.00	26.7	8.94	0.44	1.69	0.13	0.01	0.02	0.01	0.33
	R-81-133	43.4	0.70	32.1	8.07	0.19	0.47	0.10	0.01	0.05	0.04	0.43
coarse flaky talc-bearing rock	R-81-110A	53.8	0.10	30.2	4.50	0.08	0.04	0.10	0.01	0.02	0.05	0.13
	R-81-116A	53.4	0.25	30.3	4.49	0.08	0.17	0.10	0.01	0.01	0.02	0.21

* Average concentrations were not calculated because not enough samples were analyzed to permit statistical treatment.

TABLE 10. MgO/CaO Ratios of samples from Henderson deposit

Sample No.	MgO/CaO ratio	rock type*
R-81-52	2.8	steatite
R-81-110	3.2	steatite
R-81-110A	6.7	coarse flaky talc
R-81-112	0.7	tremolitic, micaceous, dolomitic marble
R-81-116A	6.7	coarse flaky talc
R-81-120	1.6	tremolitic, micaceous, dolomitic marble
R-81-121	3.0	steatite
R-81-129	2.4	tremolitic, micaceous, dolomitic marble
R-81-133	4.0	steatite
R-81-139	1.0	shear zone

*Detailed mineralogical descriptions are given in the Appendix III.

TABLE 11. MgO/CaO Ratios of samples from New Conley (341 foot level) drift

Sample No.	MgO/CaO Ratio	Rock Type*
CON-82-2	1.3	aphanitic serpentized marble
CON-82-3	0.9	aphanitic serpentized marble

*Detailed mineralogic descriptions are given in the Appendix III.

Fig. 17 - Linear relationship between CaO and MgO content in the hand specimens from the Henderson deposit. Line was established by method of least squares. Coefficient of co-relation (r) is -0.925 . It was determined by product-moment method. Sample R-81-112 was not used in calculations (for description of the samples see Table 6).

Fig. 18 SiO_2 - CaO - MgO diagram of rocks from Henderson and New Conley deposits.

Symbols: T - coarse, flaky talc-bearing rock; S - steatite; H - tremolitic micaceous marble; C - transition zone between coarse, flaky talc-bearing rock and tremolitic micaceous marble; F - tremolitic micaceous marble from a shear zone; N - New Conley marble macroscopically similar to steatite.

of coarse talc specimens, steatite and tremolitic micaceous marble. It permits also convenient comparison of the chemical composition of the above described rocks with the chemistry of the theoretical talc.

Typical samples of the coarse flaky talc-bearing rock, steatite and tremolitic micaceous marble have similar proportions of SiO_2 , MgO and CaO (Fig. 18). CaO concentrations are highest in the tremolitic micaceous marble and lowest in coarse, flaky talc-bearing rock.

Steatite has intermediate SiO_2 - MgO - CaO proportions except the sample R-81-133. This deviation from normal is related to unusually high serpentine content of the rock.

Coarse, flaky talc-bearing rock is characterized by lower CaO concentrations than steatite and micaceous tremolitic marble. However, a micaceous tremolitic marble from a shear zone is impoverished in SiO_2 and enriched in CaO in relation to typical tremolitic micaceous marble.

Contact zone (c) between coarse, flaky talc-bearing rock and tremolitic micaceous marble (sample R-81-110 of Fig. 18) has higher CaO and lower SiO_2 proportions than the coarse, flaky talc specimens, but higher SiO_2 and lower CaO content than tremolitic micaceous marble. Coarse, flaky talc-bearing rock and steatite are substantially different from theoretical talc*. The difference is caused by the presence of various accessory minerals dolomite, tremolite, mica, serpentine even in the best coarse, flaky talc-bearing samples.

Samples from the New Conley deposit (CON-82-2 and CON-82-3) have very low SiO_2 concentrations if compared with the rocks of the Henderson deposit.

* Calculated composition of theoretical (stoichiometric) talc (Roe 1975).

6.5 Chemical zoning across the Henderson deposit*

Results of chemical analysis of the talc-bearing rocks (coarse, flaky talc-bearing rock, steatite and tremolitic micaceous marble-coarse, flaky talc-bearing rock contact) as well as host rock (tremolitic micaceous marble) are plotted along the idealized geological cross section (Fig. 19).

SiO₂ content is variable and does not follow any clear cut trend. Al₂O₃ is least abundant in the coarse, flaky talc-bearing rock and increases outward. Highest concentrations correspond to the tremolitic-micaceous marble specimens. CaO, Na₂O, K₂O, TiO₂, MnO, Fe (as Fe₂O₃) and possibly S follow the same trend as Al₂O₃. Variations in loss on ignition (L.O.I.) trend cannot be easily interpreted. Shear zones have a very distinct chemical character from the tremolitic micaceous marble. They contain less SiO₂, Na₂O, and more Al₂O₃, CaO, K₂O, TiO₂, S, Fe (as Fe₂O₃). L.O.I. of the shear zone is also higher than than of tremolitic micaceous dolomite.

6.6 Chemistry of talc ore and host rock from Henderson deposit compared to other talc occurrences in carbonate rocks in North America.

The distinction between chemical analysis of the hand specimens and chemical analysis of "mill run" is necessary to interpret correctly the following data.

Chemical analysis of hand specimens may be readily compared with

* Since Henderson deposit corresponds to a portion of the talc-bearing horizon, the same findings may be true for the remainder of the talc

Fig. 19 - Variation in major elements across the Henderson deposit. (Stippled zones show a scatter in the analytical results for a given rock type.)

TABLE 12. Chemical composition of talc ores from Henderson and Conley Deposits

Sample Description	MgO	SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	L.O.I.	CO ₂	H ₂ O ⁺	H ₂ O ⁻	References
Henderson Deposit (Cantal 325)*	25-28	42-45	9.12	2-3	0.5-1	10-12	-	-	-	Richardson (1981)
Henderson Deposit Cantal Pg*	29-32	43-46	9-9.5	0.7-1	0.2-0.3	8-10	-	-	-	Richardson (1981)
Henderson Deposit (Mill Run)	27.83	52.02	6.01	2.00	0.18	-	7.34	4.20	0.24	Wilson (1926) Collected by G.H. Gillespie
Henderson Deposit Crude Talc**	29.63	53.92	5.02	0.32	0.36	-	5.51	5.05	-	Wilson (1926) Collected by H.S. Spence
Conley Deposit (Mill Run)	29.48	52.62	5.42	1.66	0.22	3.41	6.89	-	-	Spence (1940)
Conley Deposit Crude Talc**	31.72	56.32	2.36	0.06	0.20	5.18	3.99	-	-	Spence (1940)
Conley Deposit Crude Talc**	26.58	51.75	5.7	1.75	-	7.90	5.90	-	-	Spence (1940)
Pure Talc (theoretical)	31.89	63.36	-	-	-	4.75	-	-	-	Roe (1975)

* Two classes of talc, established mainly by the brightness of the ground powder (commercial names) are sold by ~~Canada~~ Talc Industries (average for several mill runs).

** hand specimen

- not determined

Fig. 20 - Henderson deposit compared to other occurrences of talc in carbonate rocks.

1 - (shaded area) typical micaceous tremolitic marble from Henderson deposit; 2 - (hatched area) composition of talc produced by Canada Talc Industries (Henderson and Conley deposits); 3 and 4 - coarse, flaky talc (hand specimens) Henderson deposit; 5 - Texas talc; 6 - average talc ore, Talcville, Gouverneur District, New York; 7 - average talc ore, Fowler, Gouverneur District, New York; 8 - talc from Yellowstone Mine (Montana); 9 - talc from Vermont; 10 - white talc, Murray County, Georgia; 11 - highly tremolitic talc from Silver Lake Mine, San Bernardino County, California. Compiled from Roe (1975) and Engel and Wright (1971), except for data from Henderson deposit.

corresponding rock types; however, this type of sample does not give accurate information about bulk composition of a sampled deposit.

Mill run analysis represents better average composition of the deposit. Mill run samples from the Henderson type deposits are a mixture of coarse, flaky talc ore, steatite and some tremolitic micaceous marble.

The variation in the chemistry of the talc ore (Table 12) may be explained by:

- a) variation in a degree of ore dilution (increase in degree of dilution with increasing depth of slopes, with increasing age of the mine, hand picking of the ore in early years of the production, other modifications in the mining and milling practices);
- b) increase in the CaO content of the talc-bearing rocks may be related to the depth. Part of the calcite could have been dissolved in near surface environment by supergene circulation of fluids. A sulfide smell (usually associated with the oxidation of sulphides) is intense on the seventh level, near the water discharges. This suggests unusually high acidity of the water in the carbonate environments;
- c) difference in the composition of protore;
- d) variation in unknown parameters of the talc forming process.

6.7 Henderson deposit compared with other talc occurrences in carbonate rocks in North America

Chemical compositions of the talc ore and host rock (tremolitic micaceous marble) of the Henderson deposit are compared with chemical

composition of talc bearing ("talc ore") rocks from other well-known North American carbonate-hosted talc deposits (Fig. 20). Chemical composition of the tremolitic micaceous marble is shown by shaded area (1)*.

Chemical composition of the commercial talc produced from Henderson and Conley deposits is represented by the hatched area (2). The chemical analyses of coarse, flaky talc (3,4) compare favourably with talc produced in Texas (5) and New York (6 and 7) states.

Talc ore from Texas and New York have nevertheless higher SiO_2 content than samples of best coarse, flaky talc ore from Henderson deposit. Steatite from the Yellowstone Mine, Montana (8) is exceptional since it corresponds closely to the theoretical talc. Vermont talc product (9) has significantly lower SiO_2 content than products from all previously described locations and does not contain any CaO . Highly tremolitic talc ore from Silver Lake Mine, San Bernardino County, California, plots very near to composition of the theoretical tremolite. Minor reduction of the CaO component in tremolitic micaceous dolomitic marble may produce material chemically equivalent to the talc bearing materials produced from principal carbonate hosted talc deposits of North America (with the exception of the talc from Vermont).

This brief comparison should be considered only as tentative, since it is based mostly on the talc material produced. It does not consider the variations in the mining and milling methods or variations in processing.

* Numbers in parentheses correspond to the legend of Fig. 20.

Analysis of the several hand specimens from each deposit would probably provide a better basis for geochemical comparison of ores from above mentioned deposits.

6.8 Summary

Although not enough data was gathered to fully understand the geochemistry of Henderson and Conley deposits, present data suggest that:

- a) there exists a negative correlation between MgO and CaO content;
- b) MgO content of coarse, flaky ore is higher than that of a typical dolomite;
- c) there exists little variation in composition between the individual samples of the coarse, flaky talc ore;
- d) there exists geochemical zoning around Henderson deposit (either related to the process of talc formation or to geochemistry of pre-metamorphic materials). This variation is summarized in Figure 19;
- e) the ore from other well-known carbonate hosted talc deposits could have been formed from the materials chemically similar to coarse micaceous dolomitic marbles of the Henderson area.

CHAPTER 7: FORMATION OF TALC AND TALC DEPOSITS

7.1 Background

Talc deposits are associated with ultramafic, mafic and carbonate rocks. This study is concerned with talc deposits associated with carbonate host rocks of sedimentary origin.

A literature survey indicates that talc deposits of this type may be formed by five major processes:

- a) precipitation of talc on the seafloor
 - near a hot submarine discharge related to volcanic activity
 - in an evaporitic depositional environment
- b) hydrothermal vein formation or alteration of carbonate host rock by hydrothermal activity
- c) prograde metamorphism of siliceous dolostone
- d) prograde metamorphism of siliceous sedimentary magnesite
- e) retrograde metamorphism.

7.1.1 Formation of talc on the seafloor

Talc has been observed on the seafloor near hot submarine discharges and in marine evaporitic environments (Costa et al. 1980).

Talc occurrences associated with Zn-Cu sulphide deposits in the Matagami mining district of Quebec have formed from the reaction of discharge of silica-rich fluids with the metal bicarbonate species of ocean water according to reaction (Costa et al. 1980):

Talc or serpentine cannot be formed at room temperature, but can be readily formed at temperatures of 90°C and above, from precursors such as sepiolite (Bricker 1973).

The following reaction may be responsible for sepiolite precipitation in the above described environment (Costa et al. 1980):

Sepiolite may be readily transformed to talc (Costa et al. 1980). Talc with sulphides has been recorded in Guaymas Basin (Lonsdale 1978), in the Sea of Japan (Shirozu 1974) and in solution vents associated with metalliferous sediments in Atlantis II Deep, Red Sea (Zierenberg and Shanks 1983, Costa et al. 1983).

Authigenic talc and sepiolite have been observed within evaporite deposits (Alderman and Van der Borch 1960, 1961, Fuchstbauer and Bodine 1972, Steward 1963, Wollast et al. 1968, Van der Borch 1976).

The stability fields of sepiolite, serpentine, talc and amorphous silica, compared with seawater and interstitial waters in modern surface sediments (Fig. 21) indicate that all the Mg-silicates noted above could be stable in modern marine sediments and that pH is an important control for stability of talc, sepiolite and serpentine (Costa et al. 1980).

7.1.2 Hydrothermal ("vein forming") activity

A hydrothermal origin has been advanced to explain the genesis of talc deposits in a wide variety of geological environments (including

Fig. 21 - Solubility relations of magnesian silicates in aqueous solutions (25°C, 1 bar total pressure). Solutions plotting above curve 1 will precipitate sepiolite, above curve 2 a serpentine mineral (chrysotile). Curves 3 and 4 illustrate talc and amorphous silica saturation. Waters plotting in the solution field should dissolve all of the above minerals. Area A represents the range of conditions in surface seawater and area B the range in seawater trapped in modern marine sediments (Costa et al. 1980).

2

57

0

NEED

Fig. 22 - Geology of the Trimouns deposit

Legend - M: Gneiss, migmatites and mica schists (footwall)
 E: Lenses (same lithology as footwall)
 TA: Talc with variable proportions of chlorite
 T: "chloritographitic" schist with intercalations of dolostone (hanging wall).

(Fortune et al. 1980)

The deposit is composed essentially of talc and chlorite. The main deposit is a lens which dips 40° to 80° (Fig. 23). The lens is irregular, its thickness varies from 9 to 80 metres and it can be traced for 5 km (Fortune et al. 1980). It corresponds to a shear zone which was permeable to percolating solutions (Fortune et al. 1980).

The Trimouns deposit was formed by at least two talc forming processes (Fortune et al. 1980):

- i) magnesium rich solutions reacted with aluminosilicates to form "chloritoschists" and with siliceous rocks to form talc;
- ii) silica (liberated by alteration of aluminosilicates to chlorite and by dissolution of quartz and unstable silicates) travelled in solution and altered dolomite into talc.

The source of the magnesium is not clear. Fortune et al. (1980), suggest as the most probable sources of magnesium: a) solution of deep seated dolomite; (b) dedolomitization related to formation of calcitic marbles during a period of migmatization and migration of solution to higher levels.

The temperature of the talc formation was estimated at 300°C , based on the tremolite to talc transformation (Fortune et al. 1980).

7.2 Progressive metamorphism of siliceous dolostones

Metamorphism of siliceous dolostones and limestones received much attention following Bowen's (1940) publication dealing with the subject. Bowen's (1940) systematic study of the siliceous dolomitic limestone outlined thirteen steps of increasing decarbonation with increasing temperature at constant pressure. Talc was added to Bowen's (1940) metamorphic suite by Tilley (1948).

The stability of talc has been determined by experimental methods, thermodynamic calculations and by detailed petrographic studies.

The stability of talc is dependent on the physical conditions (temperature, pressure), chemical composition of host rock, and chemical composition of the fluids. Metamorphism of a siliceous dolomitic limestone may be approximated by the $\text{MgO-SiO}_2\text{-CaO-H}_2\text{O-CO}_2$ system. An excellent synthesis of the information concerning this system was produced by Winkler (1979) and much of the following discussion is derived from his work. Assuming that the fluid pressure is 5 Kb*, original material is siliceous dolomite, the influence of impurities is negligible, and that minerals involved have ideal composition, then X-CO_2 and temperature are the factors controlling the stability of talc. Talc is stable at temperatures up to 550°C under the above conditions. The temperature required for talc formation is lowered if the mole fraction of CO_2 decreases (Fig. 23).

Three reactions may be responsible for the formation of talc in this system (reactions 1, 2, 3 in Fig. 23).

Other minerals may be formed by the progressive metamorphism of siliceous dolomite (equations 5, 9, 10, 12, 14 and 15, Table 13).

Reactions 5 and 15 may take place only if the original dolomite rock (prior to metamorphism) contained magnesite and quartz (Winkler 1979).

Reactions 9, 10 and 12 are metastable (Metz, 1976). If the pressure is other than 5 Kb the location of reactions on the T-X_{CO_2} diagrams change but the diagram nevertheless retains the same general appearance.

* 3.5 Kb or 4 Kb fluid pressure is probably more realistic in the mine if metamorphic conditions are consistent with "Idahoan" field gradient as established by Sethuraman and Moore (1973).

Fig. 23 Isobaric T - X_{CO_2} diagram at 5 Kb fluid pressure for reactions in siliceous dolostone (Winkler 1979).

TABLE 13. Metamorphic reactions in siliceous dolostone.
Reactions 9, 10 and 12 are metastable (Winkler 1979).

Literature survey indicates that there are no economic talc deposits known to have formed by metamorphism of siliceous dolostone.

7.3 Metamorphism of siliceous magnesite

The $\text{MgO-SiO}_2\text{-CO}_2\text{-H}_2\text{O}$ system is used to project compositions of metamorphic mineral assemblages of ultramafic rocks; the same system can also be applied to siliceous magnesite bearing rocks of sedimentary origin (Winkler 1979). Rocks of this type are known to form at present in Coorong Lagoon of southeast South Australia (Alderman 1965). Extensive siliceous magnesite deposits are known in Southern Pithoragarh, India (Valdia 1968). These deposits are usually planar, stratigraphically controlled, invariably associated with algal bioherms and are related to high Mg/Ca ratio in basin waters (Valdia 1968). The Mg/Ca ratio increased with time as a result of biogenic extraction and/or inorganic precipitation of CaCO_3 within the basin. Early formed carbonates are converted into high magnesium carbonates under high Mg/Ca ratio (attributed to algae growth) and high pH conditions (Valdia 1968). Interstitial talc formed from the reaction of quartz with magnesite during the metamorphism (Valdia 1968).

Important reactions to be considered in the general study of the metamorphism in $\text{MgO-SiO}_2\text{-H}_2\text{O-CO}_2$ system (described by Winkler 1979) are given in Table 14, and the corresponding equilibrium curves at fluid pressure of 2 Kb are given in Figure 24. Isobaric equilibrium curves at fluid pressures of 4 Kb, 2 Kb and 1 Kb respectively are given in Figure 26.

Isobaric equilibrium curves of reactions occurring as large mole fractions of χ_{CO_2} are presented in Figure 27. Reactions 2, 3, 4, 7, 8,

Fig. 24 - Isobaric equilibrium curves (at 2 kb) of reactions (1) through (20) in the system MgO-SiO₂-H₂O-CO₂.

Remark: The experimental data for reactions (6) and (7) have been obtained using chrysotile as the serpentine species. Using antigorite instead of chrysotile gives rise to somewhat higher equilibrium temperatures (Winkler 1979).

Fig. 25 - Isobaric equilibrium curves of the selected reactions in the low $X\text{-CO}_2$ range of the $\text{MgO-SiO}_2\text{-H}_2\text{O-CO}_2$ system at fluid pressures of 4 Kb, 2 Kb and 1 Kb respectively. Legend is same as in Figure 24 and same remark as for Figure 24. (Johannes 1969).

TABLE 14. Key reactions in $\text{MgO-SiO}_2\text{-H}_2\text{O-CO}_2$ system (Winkler 1979).*Reactions at extremely small values of X_{CO_2} :* *Reactions within a large intermediate range of X_{CO_2} between the extremes:* *Reactions at extremely large values of X_{CO_2} :*

TABLE 15. Petrogenetically important assemblages in MgO-SiO₂-H₂O-CO₂ system (Winkler 1979).

(8)	Serpentine + quartz + talc
(8/3)	Serpentine + quartz + talc + magnesite, invariant point very close to (8)
(6)	Serpentine + brucite + forsterite (first possible appearance of forsterite!)
(6/1)	Serpentine + brucite + forsterite + magnesite, isobaric invariant point very close to (6)
(7)	Serpentine + forsterite + talc
(7/3)	Serpentine + forsterite + talc + magnesite, isobaric invariant point; temperatures very close to those of (7)

Fig. 26 - Isobaric equilibrium curves of reactions occurring at large X_{CO_2} values. Horizontally ruled: enstatite + magnesite; vertically ruled: anthophyllite + magnesite (Johannes 1969).

9, 11 and 14 (Table 14) may be involved in formation of talc under favourable prevailing conditions. Petrogenetically important assemblages are listed in Table 15.

The influence of Al_2O_3 , CaO , FeO , F or other species may modify the stability fields and stabilize additional minerals (Winkler 1979, p. 162-166 and Mercolli 1980).

7.4 Retrograde metamorphism

All the reactions considered in the section on metamorphism of siliceous dolostone and magnesite can proceed in both directions. Retrograde metamorphism, the process whereby higher grade metamorphic rocks are transformed into lower grade ones, is known to occur mainly along shear zones and fracture zones where H_2O and CO_2 may circulate (Winkler 1979). Retrograde metamorphism is treated here as an individual talc forming process mainly because it is treated as such by most practicing exploration geologists (for example, Bates 1969).

The combination of metamorphic and hydrothermal "vein forming" activity is proposed for talc formation in the Gouverneur district by Bates (1969). Bates describes (p. 332) the process as:

"The tremolite was probably formed during severe stages of regional metamorphism (Engel 1947). Its calcium, magnesium, and silica were made available by reactions between, and replacement of, favourable beds of quartzite and metadolomite. The mobile agents were hydrothermal solutions at high temperatures, probably charged with silica. Increasing intensity of metamorphism produced diopside and other anhydrous silicates. Serpentine and talc did not make their appearance until later stages of retrograde metamorphism and falling temperature at which time abundant magnesium was available in solution. Serpentine and talc, in other words, formed at the expense of earlier silicates largely as fibrous pseudomorphs after tremolite."

7.5 Discussions

A literature survey indicates that the genesis of talc deposits is believed to be mainly of a hydrothermal vein forming. No reference to economically significant talc deposits exists in which metamorphism of siliceous dolomite or magnesite is recognized as the main talc forming process. The same applies for the process where talc is formed by reaction of silica with metal bicarbonate near a hot submarine discharge or by precipitation in evaporitic environment. Retrograde metamorphism is mostly suggested on the basis of retrograde textures observed in thin sections. No significant information exchange exists between contemporary researchers in petrology and practicing economic geologists of the industrial mineral sector. The dominance of the hydrothermal vein forming process may be therefore only apparent.

CHAPTER 8: ORIGIN OF THE HENDERSON TALC DEPOSIT

The Henderson deposit is traditionally regarded as hydrothermal, (Table 16). Hewitt (1968) writes:

"The best explanation as to the origin of these talc deposits is that of Wilson (1926) who regarded them as hydrothermal replacement deposits. Conformable sheet-like bodies of talc were developed from the Grenville dolomite by the introduction of hydrothermal solutions that probably originated from the neighbouring Moira granite. These hot-water silica-bearing solutions ascended fractures and faults on the south limb of the anticline and altered the dolomite first to tremolite and then to talc. Evidence of this dolomite-tremolite-talc transition can be seen in thin sections of the rocks from the deposit. Subsequent folding and faulting is responsible for the crenulation, thickening, and offsetting of the talc ore sheets. The madocite dikes and the hydrothermal solutions probably had a common origin in the Moira granite magma. The talc does not appear to be particularly associated genetically or spatially with the dikes themselves."

8.1 Critical observations

Any genetic model which attempts to explain the origin of the Henderson, Conley and East deposits must satisfy the following stratigraphic, structural, morphological, petrological, mineralogical and geochemical restrictions.

Stratigraphic criteria:

1. Henderson, Conley and East deposits are related to the same stratigraphic horizon, near the metapelite-marble transition.
2. Talc deposits occur in micaceous tremolitic marbles.
3. Talc deposits occur near quartzite with stromatolitic textures.
4. At least one Zn, Cu, deposit is located on the same stratigraphic horizon in the Madoc area (Simandl, in preparation).
5. Footwall, hanging wall, and steatite contain fine and regular sedimentary laminations.

TABLE 16. Origin of the Henderson Talc Deposit
(compilation from the literature)

AUTHOR	YEAR	POSTULATED ORIGIN
Wilson	1926	Silication of the dolomite through the action of solutions emanating from the Moira granite. (Openings now occupied by dykes were probably the channels along which these emanations ascended).
Spence	1940	Same as Wilson, 1926.
Sandomirsky	1954	Enumerates all the sources of MgO and SiO ₂ considers several origins but in the end also favours Wilson's 1926 theory.
Hewitt	1957 p. 21	Essentially same as Wilson 1926, but the silica-bearing aqueous solutions ascended through fractures and faults. Hewitt also writes: "Madocite dykes do not appear to be particularly associated genetically and spatially with the ore themselves".
Roscoe	1966 p. 52	Roscoe concluded: "Conditions needed to form talc ore are: abundant MgO, SiO ₂ and fairly low temperatures and pressures. Since these conditions appear to have existed through the mine area to a limited extent, some other control is necessary to concentrate or idealize these conditions. This control is structure. The structural control may be faulted-fold or folded-fault."

6. Small scale cross bedding was found in steatite blocks.
7. Chert layers containing disseminated pyrite and dravite porphyroblasts are common in the tremolitic micaceous marble.

Structural and morphological restrictions:

8. The contact between ore and host rock may be sharp or gradual over up to 1.7 m. The contacts between coarse, flaky talc ore and steatite do not follow individual ~~individual~~ sedimentary laminations.
9. Deposits are stratabound and form sheets and lenses of variable thickness.
10. The talc-bearing horizon is folded and offset by faulting.
11. Amphibolite dykes and micaceous sulphide-bearing veins cut the laminations within tremolitic, micaceous marble and steatite (some dykes are folded).
12. Dykes or blocks of dyke material occur inside the talc ore.
13. Dykes cannot be correlated between the hanging wall and footwall of the Henderson deposit, but dykes were reported to cut the ore in the Conley and East deposits.
14. Dravite porphyroblasts in the host rock are flattened (forming "pancakes") and oriented parallel to the rock cleavage.
15. Dravite porphyroblasts in the coarse talc ore and steatite are not deformed, or only slightly deformed.

Petrologic and mineralogic restrictions:

16. Coarse talc flakes are pure white (probably low in iron)
17. Serpentine is present in talc ore.
18. Brucite is present in the mine area.

19. Tremolite, talc and quartz occur in steatite. Because these minerals were recognized in X-ray data, it is not clear if all three are in contact.
20. Talc is present as pseudomorphs after tremolite or actinolite (retrograde textures).
21. Two generations of tremolite-actinolite minerals (first strongly altered and second fresh) were observed in black "phyllite" beds.
22. Quartz-talc-calcite assemblage was observed in stromatolitic quartzite with stromatolitic texture.
23. The talc ore is of two textural types:
 - a) coarse, flaky white talc ore without sedimentary textures
 - b) laminated, fine-grained to aphanitic steatite.
24. Calcite is absent in coarse, flaky talc ore, minor or absent in steatite, but abundant in surrounding micaceous tremolitic marble.
25. Remnants of dolomite and tremolite crystals are visible in coarse, flaky white talc ore.
26. The major minerals of Henderson type ore are: talc (71%), dolomite (24%); minor constituents are mica, serpentine, tremolite, chlorite, vermiculite and quartz. Calcite is absent or in trace. N.B. Serpentine may be a major constituent in steatite.
27. Dravite phenocrysts contains quartz inclusions if embedded in chert, and tremolite inclusions if embedded in the marble.
28. Tremolite is widespread in the mine area, but talc concentrations are very localized.
29. Isobaric divariant mineral assemblages (such as phlogopite-calcite, tremolite-calcite) are abundant; however, coexistence of reactants and products (such as phlogopite-calcite-dolomite-quartz, K-

feldspar, tremolite-calcite-dolomite-quartz) is uncommon.

30. Vertical, mineralogical zoning within the Henderson and East deposits is characterized by higher concentrations of tremolite and calcite with depth.

Geochemical restrictions:

31. Chemical compositions of tremolitic micaceous marble and steatite are similar to composition of coarse, flaky talc ore.
32. Chemical zoning perpendicular to strike of the deposit is well developed.
33. The MgO/CaO ratios in coarse, flaky talc ore is unusually high.
34. Negative correlation exists between MgO and CaO.
35. Homogenization in chemical composition is evident as one approaches the talc deposit.

8.2 Applicability of genetic models to Henderson-type talc deposits

This section consists of three distinct parts. The first part relates the 35 criteria previously described to genetic models presented in Chapter 7.

The second part combines selected criteria to generate additional restrictions regarding the time of talc formation, conditions that prevailed at the time of deposition of sediments which formed the protolith, closed vs. open system, character of talc-forming fluid(s) and upper temperature limits of talc formation.

The third part contains a newly proposed genetic model which reconciliates the 35 criteria, the limits generated by combining selected criteria, and tectonic framework proposed by Moore and Thompson (1980).

TABLE 17. Thirty five criteria in relation with models described in Chapter 7.

Model		Supporting Features	Neutral	Negating Features
Precipitation of the talc precursors on the sea floor	exhalative	1, 2, 3, 4, 5, 6, 7, 9, 11, 17, 24, 28, 33	10, 11, 12, 13, 14, 15, 18, 19, 22, 26, 27, 29, 30, 31, 32, 34, 35	8, 16, 20, 21, 23, 25
	evaporitic	1, 2, 3, 4, 5, 7, 9, 16, 17, 24, 28, 33	10, 11, 12, 13, 14, 15, 18, 19, 22, 26, 27, 29, 30, 31, 32, 34, 35	6, 8, 20, 21, 23,
Prograde metamorphism of magnesite bearing carbonate horizon		1, 3, 4, 5, 7, 9, 16, 17, 19, 24, 28, 33, 34	2, 6, 10, 11, 12, 13, 14, 15, 18, 22, 26, 27, 29, 31, 32, 35	8, 20, 21, 23, 25, 30
"Normal" prograde, regional metamorphism of siliceous dolostone (without magnesite)		1, 16, 19, 22	3, 4, 5, 6, 7, 10, 11, 12, 13, 14, 15, 27, 29, 31, 32, 35	2, 8, 9, 17, 18, 20, 21, 23, 24, 25, 26, 28, 30, 33, 34, 35
Hydrothermal metasomatic origin such as proposed by Wilson (1926)		8, 17, 23, 24, 25, 28, 29, 30, 32, 35	1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 12, 13, 14, 15, 16, 18, 19, 20, 21, 26, 27, 31, 32, 33, 34	22
Retrograde metamorphism		2, 8, 17, 18, 20, 23, 25, 28, 29, 30, 32, 33, 35	1, 3, 4, 5, 6, 7, 9, 10, 11, 12, 13, 14, 15, 16, 19, 21, 22, 24, 26, 27, 31, 34	21

8.2.1 Relations between 35 criteria and genetic models presented in Chapter 7

Stratigraphic, structural, morphological, petrological, mineralogical and geochemical criterions (1-35), enumerated on previous pages, are used to evaluate the applicability of genetic models presented in Chapter 7. The results are recompiled in Table 17.

A major disadvantage of such an approach resides in the possibility, that a "statistically-inclined" reader may consider the negative features only. Such a reader may incorrectly conclude, that hydrothermal, vein forming, activity or retrograde metamorphism explain best the origin of talc deposits, because these models correspond to lowest numbers of negating features. A brief discussion of individual models presented in Chapter 7 follows.

8.2.2 Precipitation of the talc or talc precursors on the sea-floor

Precipitation of the talc and/or talc precursors on the sea-floor takes place in two distinct environments:

- a) in topographic-lows associated with submarine exhalative activity
- b) in évaporitic basins

These two depositional environments are difficult to distinguish in metamorphosed carbonates. It is possible that these environments overlap in the Henderson Mine area. Precipitation of the talc and/or talc precursors on the sea-floor does not explain the following features: sharp and gradual contacts between the steatite and the host rock (tremolitic micaceous dolomitic marble) locally discordant contacts between white, coarse, flaky talc ore and steatite, presence of talc

pseudomorphs after tremolite or actinolite, two generations of tremolite-actinolite solid solution members. In black talc-bearing phyllite, strongly altered remnants of dolomite and tremolite crystals in white coarse, flaky talc ore, presence of two texturally distinct types of talc ore, abundance of isobaric divariant mineralogic assemblages and uncommon coexistence of reactant and products, vertical mineralogical zoning. High MgO, low FeO talc is not typical in the hydrothermal systems related to volcanic activity. On the other hand, this model explains particularly well all the stratigraphic and major morphological features.

8.2.3 Metasomatic (vein forming) activity

Variants of this model were previously proposed for Henderson-type talc deposits by Wilson (1926), Spence (1940), Sandomirsky (1954), and Hewitt (1957). External sources of magnesium and silica are required in all these cases (Table 16).

Simple metasomatic talc-forming activity, as presented by above authors does not explain with satisfaction most of stratigraphic criteria and high-MgO/CaO ratio of the fluids required for talc formation.

Retrograde, post-tremolite textures observed in coarse, flaky white talc ore are probably related to a distinct period of post-tremolite metasomatic or metamorphic activity of retrograde nature, since talc pseudomorphs after tremolite occur in talc horizon only.

In situ sources of magnesium and silica were proposed for such metasomatic processes as a result of the underground mapping of the Henderson deposit. In situ magnesium sources making this hypothesis more appealing are:

- primary concentrations of magnesium rich sediments (magnesite, hydromagnesite, serpentine, talc, sepiolite or other talc precursors on the sea floor)
- replacement of dolomite by magnesite* as described and summarized by Rosenberg and Holland (1964) and Rosenberg and Mills (1966).

Magnesium concentrating processes as noted above explain the high MgO/CaO ratio, and negative correlation between CaO and MgO.

Subsequently talc may be formed by several metasomatic or metamorphic reactions which derive magnesium and silica from the protolith of the talc-bearing horizon.

Remnants of tremolite and dolomite crystals and absence of calcite within coarse, flaky white talc ore indicate that if magnesium was not preconcentrated prior to the talc formation, then calcite was not stable at the time of talc precipitation or it was leached out later.

Abundance of tremolite, dolomite, serpentine and presence of calcite in traces within steatite indicate that the host rock did not have a composition of relatively pure magnesite and that reactions other than those presented in Table 14 must have been involved.

* Rosenberg and Mills (1966) summarized their experimental investigations explaining replacement of dolomite by magnesite as follows:

1. Attack of pre-existing dolomite by CO₂ bearing solutions at temperatures below 200°C resulting in solutions with a Ca:Mg ratio of unity.
2. Heating of these solutions to temperatures in excess of 200°C, resulting in the replacement of host rock dolomite by magnesite with production of Ca-rich solutions".

This process does not require outside source of MgO .

8.2.4 Prograde metamorphism of siliceous dolostone without magnesite

Prograde metamorphism affected the Madoc area (Carmichael, Moore and Skippen 1978). It contributed indirectly to the formation of talc deposits; however, normal regional metamorphism of carbonate rocks in presence of high- CO_2 fluid cannot explain: presence of serpentine within steatite, two generations of tremolite-actinolite minerals, absence of calcite within coarse, flaky talc ore, widespread distribution of tremolite vs. localized occurrence of talc in the mine area, abundance of isobaric, divariant, mineralogic assemblages, vertical and horizontal zonations, unusually high talc concentrations in ore, high MgO/CaO ratio, negative correlation between MgO and CaO , and homogenization in chemical composition as one approaches the talc deposit.

Serpentine is abundant and widespread in steatite. It requires the presence of fluid with low mole fraction of CO_2 and high mole fraction of H_2O (Fig. 25). Such fluid cannot be derived by devolatilisation of marbles during metamorphism. However, it may have been derived by devolatilisation of underlying pelitic rocks or nearby sedimentary rocks of volcanic origin.

Presence of talc pseudomorphs after tremolite or actinolite, and remnants of tremolite and dolomite within coarse, flaky talc ore cannot be explained by prograde metamorphism.

Two generations of tremolite-actinolite minerals in black "phyllite" (first strongly altered and second fresh) do not have their equivalents within coarse, flaky talc ore, where all amphiboles are strongly altered.

Absence of calcite within the coarse, flaky talc horizon cannot be explained by reactions known to occur during prograde metamorphism of siliceous dolostone (Fig. 23) because all of these talc-forming reactions involve simultaneous formation of talc and calcite.

Reaction 1 of the Table 13 corresponds best to the conditions of regional metamorphism in the mine area. Given optimum concentrations of dolomite and quartz in siliceous dolostone without impurities, this reaction produces a marble containing 56% talc by weight or 62% talc by volume. The above talc concentrations are inferior at least by 9% to talc levels observed in ore of the Henderson deposit (Table 4), without considering dilution factor during mining.

Widespread distribution of unaltered tremolite within the mine area is in contrast with altered tremolites within talc horizon, and with the very localized nature of the talc-bearing horizon. Conditions that prevailed at the time of talc formation are, therefore, related to regional metamorphism only indirectly or partially.

Abundance of isobaric divariant mineralogic assemblages and uncommon coexistence of reactions and products within ore and host rock suggest that external buffering (metasomatic activity) took place along the talc horizon.

Vertical mineralogical zonation, chemical horizontal zonation, unusually high MgO/CaO ratio, negative correlation $MgO - CaO$, and homogenization in chemical composition as one approaches the talc deposit are other features that cannot be explained by metamorphism of impure siliceous dolostone, which does not contain magnesite or other magnesium-bearing minerals (of sedimentary or metasomatic origin).

8.2.5 Prograde metamorphism of magnesite bearing siliceous carbonate

The prograde regional metamorphism of a magnesite bearing carbonate bed surrounded by a siliceous dolostone does not explain textural variations in ore, retrograde textures and vertical mineralogical zonation within the deposits.

Presence of two types of talc ore (coarse and flaky without preserved sedimentary textures and second aphanitic and laminated) indicate at least two different processes of talc ore formation.

Presence of talc pseudomorph after tremolite-actinolite, and remnants of tremolite-actinolite and dolomite within coarse flaky, talc ore are best explained by retrograde metamorphism or metasomatism. Vertical mineralogical zonation within the deposit over the distance of less than 250 m is probably better explained by metasomatic overprint rather than by primary variation in composition in the protolith.

The prograde regional metamorphism of a magnesite bearing bed is in agreement with any other criteria listed in Table 17.

8.2.6 Retrograde metamorphism

Retrograde metamorphism is the process whereby higher grade metamorphic assemblages are transformed into lower grade ones (Winkler 1979).

This definition alone indicates that, in metasedimentary rocks, retrograde metamorphism must be preceded by prograde metamorphism, and cannot be a sole process involved in formation of talc deposits.

Retrograde metamorphism is not related to any of the stratigraphic features; however, it is the only process that explains the retrograde textures in the ore. It is in agreement with the remaining observations

(Table 17). It is also remarkable that given ideal conditions (T, P, fluid, initial composition of the protolith, reaction may produce ore with talc grades comparable to those reported in Table 4.

8.3 Additional restrictions

None of the above genetic models explains all the features of the Henderson type deposits; this combination of above models is required to satisfy all the 35 criteria.

Before discussing a combined model, some of the criteria will be considered together to obtain additional restrictions on the probable time of talc formation, sedimentary conditions that prevailed during the deposition of the talc horizon, the type of fluids, applicability of closed versus open system and upper temperature limit of the talc formation.

8.3.1 The time limits on the period of talc formation

Features 8, 10, 11, 12, 13, 14 and 15 set time constraints on the formation of the talc deposit.

The discordant nature of white coarse, flaky talc ore-steatite contact suggests that coarse, flaky white talc ore post-dates steatite (Fig. 27).

Folding and offsetting of talc-bearing horizon suggest that talc deposits were formed prior to final stages of tectonic activity (Fig. 27).

The above argument is further supported by cross-cutting relationships between talc horizon and late, folded amphibolite and micaceous sulphide-bearing veins.

Figure 27. Relative chronology in the Henderson area and its relation to Grenvillian orogenic cycle.

Sources of information:

Moore and Thompson (1980)

Time periods estimated on the basis of information from Bain (1960), Davidson et al. (1979) and Bell and Blenkinsop (1980).

Fresh tremolite inclusions preserved within dravite phenocrysts indicate that tourmaline crystallized during the period of prograde metamorphism, probably related to intrusion of Moira granite or to Ottawa orogeny (Fig. 27). Flattening of dravite porphyroblasts within silicated marbles and orientation of these deformed porphyroblasts parallel to the rock cleavage, suggest that dravite is either pre-deformational or syn-deformational.

Dravite porphyroblasts in talc-bearing rocks are undeformed or less deformed than dravite porphyroblasts within silicated marbles. It suggests that tourmaline phenocrysts were protected from effects of tectonic stress by ductile medium (talc and/or serpentine). At least some talc and/or serpentine must have formed prior to period of intense tectonic activity associated with Ottawa orogeny, unless two generations of stratigraphically controlled dravite concentrations exist in the Henderson Mine area.

8.3.2 Conditions that prevailed during the deposition of the talc protolith

The talc deposits are located within the transition zone between metapelites and marbles and are associated with stromatolites suggesting shallow marine, probably evaporitic environment. The talc deposits are stratigraphically associated with a Zn-Cu stratabound deposit. Cherty bands and dravite-sulphide horizons in similar environments are considered lateral equivalents of the iron formations associated with exhalative massive sulphide deposits (Slack 1982). An unusually high MgO/CaO ratio is consistent with the information on iron formations in other parts of the Grenville Province (Gauthier 1982, Gauthier 1981).

However, high MgO/CaO ratio may be also explained by biogenic activity in evaporitic marine environment (Valdía 1968).

8.3.3 Closed versus open system

The transformation of a closed metamorphic system into an open system, where the composition of the fluids is controlled by large external reservoirs is well documented (Kerrick 1974). If the fluids are externally buffered, isobaric divariant assemblages are abundant and the coexistence of reactants and products is unlikely (Rice and Ferry, 1982). Such is the case near the Henderson type talc deposits, Madoc.

The area studied was affected by prograde regional metamorphism (Carmichael, Moore and Skippen 1978). Homogenization of the bulk chemical composition of the talc ore in the area of Henderson deposit (Fig. 19) and absence of coexisting reactants and products may be attributed to equilibration of the rock with large volume of the fluids supplied by large external reservoir.

Other observations supporting these arguments are: nearly monomineralic nature of coarse, flaky talc ore, locally discordant contact between coarse, flaky white talc ore and steatite, absence of calcite within coarse, white talc ore and gradual increase in the calcite content outward from the deposits, negative correlation between MgO and CaO content (Fig. 17), comparatively widespread distribution of coarse tremolite in the mine area and localized distribution of coarse, white talc ore within the deposits, coexistence of fresh tremolite-actinolite minerals and altered tremolite-actinolite minerals within black talc ("phyllite") horizon, retrograde textures within white coarse, talc ore and "phyllite".

8.3.4 Character of fluids and upper temperature limit of the talc formation

Features 17, 18, 22 and 26 indicate that fluids present at the time of formation of steatite and of coarse, flaky talc ore were rich in H_2O .

Serpentine was identified as a major component of steatite and as a minor component of coarse white talc ore. It indicates that ore forming fluid had extremely low molar fraction of CO_2 (Fig. 24, and Table 14). Brucite is also an excellent indicator of low molar fraction of CO_2 (Table 14); however, it is very scarce in Henderson Mine area, and may be related to circulation of post-talc ore fluids only. Quartz-talc-calcite assemblage was observed within stromatolitic horizon less than 10 metres from the talc horizon. This assemblage indicates that temperature and mole fraction of CO_2 were confined in the area limited by curves 1 and 2 (Fig. 23). If steatite was formed during prograde regional metamorphism, then quartz-talc-calcite assemblage suggests that temperature remained under $500^\circ C$. Tremolite and dolomite hosted in steatite, in coarse, white flaky talc ore and in "phyllite" are altered to talc indicating possible variations in fluid composition over a short distance.

The same fluids may be also characterized by considering activities of SiO_2 , Mg^{++} and Ca^{++} . T-X diagram shows that fluids which formed talc deposits were very rich in water (Fig. 23 and Table 14). If the temperature of talc formation was inferior to $500^\circ C$, the system was open, total fluid pressure was low and x_{CO_2} approached 0, the system may be approximated by logarithmic activity diagram for $CaO-SiO_2-MgO-H_2O$ system, where a_{H_2O} is 1, at constant temperature of $425^\circ C$ and total

Fig. 28. Logarithmic activity diagrams for the system $\text{CaO-SiO}_2\text{-MgO-H}_2\text{O}$ at 425°C , 0.5 Kb and $a_{\text{H}_2\text{O}} = 1$ (Frish and Helgeson 1984).

fluid pressure of 0.5 Kbar* (Fig. 28). The diagram shows that steatite could have formed under the conditions where $\log a \text{Ca}^{++}/a^{2\text{H}+} = 5$, $\log a \text{Mg}^{++}/a^{2\text{H}+} = 3.2$ and $\log a \text{SiO}_2 = -2.5$, if tremolite, talc and serpentine are in equilibrium (Fig. 28). Zone of coarse, flaky talc ore does contain little or no serpentine and is characterized by high talc concentration. This zone corresponds to higher $\log a \text{SiO}_2$, lower $\log a (\text{Mg}^{++}/a^{2\text{H}+})$ and higher $\log a (\text{Ca}^{++}/a^{2\text{H}+})$ than surrounding steatite (Fig. 28). It is therefore possible that both coarse, white, flaky talc and steatite developed from tremolitic dolomite by metasomatic activity and that mineralogical zoning of the deposit reflects progressive changes in SiO_2 , Ca^{++} or Mg^{++} activities.

8.4 Proposed Model

It is proposed that the talc deposits were formed by metamorphism and/or metasomatism related to the metamorphism of magnesium-bearing sediments.

The proposed model with or without minor variations satisfied criteria 1 to 35, time limits of the deposit's formation, sedimentary conditions that prevailed at the time of deposition of protore, the nature of the fluids, as well as the passage from an open to closed system or vice versa.

The events known to have occurred in the vicinity of the Henderson mine are tentatively correlated with major events that affected the Madoc area (Fig. 28).

* fluid pressure was probably lower than lithostatic pressure if the system was open.

The weakness of the model is the uncertainty about the stratigraphic position of the Henderson deposit (Fig. 7) within the rocks of the Grenville Supergroup (Table 1).

The major advantage of this model over the previously proposed models described in Table 16 is that external sources of magnesium and silica are not required.

8.4.1 Genesis of Henderson deposit

The consolidation of the Amphibian crystalline basement took place at least 1500 m.a. ago (Bell and Blenkinsop 1980).

Consolidation was followed by volcanic activity and deposition of pelitic and carbonate sediments between 1300 and 1225 m.a. ago (Moore and Thompson 1980).

Transition between pelitic and carbonate sediments consisted of sediments with high MgO/CaO ratios. It probably consisted in part of talc, serpentine, sepiolite, magnesite or by hydromagnesite and was deposited in a shallow evaporitic environment.

Synchronously, submarine hydrothermal discharges (probably related to the latest stage of volcanic activity) deposited thin, cherty sulphide-bearing layers within evaporitic sediments.

Diagenesis, lithification and metamorphism of the magnesium rich, evaporitic sediments and cherty layers took place in the early stages of Elzevirian orogeny (Fig. 27) and resulted in the formation of steatite, which acted as a zone of tectonic weakness during all subsequent events. Moira pluton was probably emplaced in the final stages of Elzevirian orogeny (Fig. 27).

Geographic association of strongly silicated marbles (coarse-tremolite zones) with granitic rocks (Fig. 5), suggests that coarse tremolite was formed by contact metamorphism.

Fine-grained, disseminated tremolite is widespread in the mine area and was probably formed during regional prograde metamorphism (Reaction 2, Table 13).

Regardless of whether boron contained in tourmaline was derived from the sedimentary clays during Elzevirian orogeny or from Moira pluton, tourmaline porphyroblasts were formed during or before Ottawa orogeny (Fig. 27). The extensional tectonic regime (corresponding to the deposition of Flinton Group within Hastings area) favoured fluid circulation by reactivating old channels (including tectonic weakness coinciding with steatite zone).

The conditions that prevailed at the time of formation of coarse, flaky talc ore are not well understood. They may be tentatively approximated by the $\text{MgO-CaO-SiO}_2\text{-H}_2\text{O-CO}_2$ closed and/or open system.

Reactions listed in tables 13 and 14, shown in Figures 24, 25, 26 and 27 were considered in order to explain genesis of coarse talc ore.

Geological setting, mineralogy, textures, high content of talc and high MgO/CaO ratio indicate that no single reaction will satisfy all the conditions. The combination of the following reactions may have taken place:

The first metamorphic reaction explains the high MgO/CaO ratio and high talc content of the ore and absence of calcite. The second reaction is proposed mainly because of the abundance of dolomite in the coarse ore and the presence of dolomite and quartz in the tremolitic micaceous marble hosting the deposit.

By itself, this reaction could not produce talc ore containing 71% talc and lacking calcite unless it was accompanied or followed by leaching out of calcite (open system).

The third reaction is retrograde. It could produce talc concentrations comparable to coarse, flaky talc ore under optimum conditions, explains retrograde textures within coarse talc ore, but it must be accompanied or followed by leaching out of calcite.

Coarse talc ore could have been also produced, at least in part, by the following reaction where SiO₂ and MgO were derived from the cherty layers and steatite:

The fluids with the H₂O content required to form talc by the first, second and fourth reactions listed above, could have been derived by regional prograde metamorphism from the underlying sedimentary rocks and/or from sedimentary rocks of volcanic origin (Fig. 7).

Syntectonic intrusions transected the talc-bearing horizon during terminal stages of the Grenvillian cycle when tectonic and metamorphic activity declined. Pre-Paleozoic uplift, partial erosion of the deposits and adjacent rocks, deposition of Paleozoic cap rock, Paleozoic erosion and deposition of unconsolidated Pleistocene sediments succeeded the formation of talc ore and affected significantly the geological setting of talc deposits.

REFERENCES

- ALDERMAN, A.R. 1965. Dolomite sediments and their environments in the southeast South Australia. *Geochimica et Cosmochimica Acta*, 29, pp. 1355-1365.
- ALDERMAN, A.R. and VAN der BORCH, C.C. 1961. Occurrence of magnesite-dolomite sediments in South Australia. *Nature*, v. 193, p. 861.
- ALDERMAN, A.R. and VAN der BORCH, C.C. 1960. Occurrence of hydromagnesite in sediments in South Australia. *Nature*, v. 188, p. 931.
- ARANITIS, S. 1967. Les gisements de talc pyreneens. Description. Essai d'interpretation de leur genese. *Bulletin du bureau de Recherches geologiques et minieres, France*, no. 1, pp. 3-118.
- BAER, A.J. 1976. The Grenville province in Helikian times; a possible model of evolution. *Philosophical Transactions of the Royal Society of London, Ser. A.*, 280, pp. 499-515.
- BAIN, I. 1960. Geology of the Grenville Belt through Actinolite, Ontario. Ph.D. thesis, University of Toronto, Toronto, Ontario.
- BATES, R.L. 1969. *Geology of the Industrial Rocks and Minerals*. Dover Publications, New York, 459 p.
- BELL, K. and BLENKINSOP, J. 1980. Whole rock Rb-Sr studies in the Grenville Province of Southeastern Ontario and Western Quebec - A Summary Report. In *Current Research, part C, Geological Survey of Canada, Paper 80-TA*, pp. 152-154.
- BLOUNT, A.M. 1982. Mineralogy of core samples Madoc, Ontario. Unpublished report, Canada Talc Industries Ltd., Madoc, Ontario, 3 p.
- BODINE, M. 1972. Layer silicates in modern marine hypersaline environment (Abstract). 21st Clay Minerals Conference, 9th annual Meeting, Clay Minerals Society, p. 19.
- BOURQUE, M.S., CROSBY, C.A., DONALDSON, J.A. and MOORE, J.M., Jr. 1982. Algal Stromatolites in the Grenville Supergroup of Eastern Ontario. Joint Annual Meeting, Geological Association of Canada, program with abstracts, v. 7, 39 p.
- BOWEN, N.L. 1940. Progressive metamorphism of siliceous limestone and dolomite: *Journal of Geology*, 48, pp. 225-274.
- BRICKER, O.P., NESBITT, H.W. and GUNTER, W.D. 1973. The stability of talc: *American Mineralogist*, v. 58, pp. 64-72.
- BROWN, R.L., CHAPPELL, J.F., MOORE, J.M., Jr. and THOMPSON, P.H. 1975. An ensimatic island arc and ocean closure in the Grenville Province of southeastern Ontario, Canada. *Geoscience Canada*, 2, pp. 141-144.

- CAPDECOMME, L. 1950. Sur la genese des talcs pyrénéens. Bulletin de la Société d'Histoire naturelle de Toulouse, 85, pp. 313-316.
- CARMICHAEL, D.M., MOORE, J.M., Jr. and SKIPPEN, G.B. Isograds around the Hastings metamorphic "low". In Toronto '78: Field trips guidebook. Edited by A.L. Currie and W.O. Mackasey, Geological Association of Canada, pp. 325-346.
- COSTA, U.R., BARNETT, R.L. and KERRICH, R. 1983. The Mattagami Lake Mine Archean Zn - Cu Sulfide Deposit, Quebec: Hydrothermal Coprecipitation of Talc and Sulfides in a Sea-floor Brine Pool - Evidence from Geochemistry, $180/160$ and Mineral Chemistry. Economic Geology, 78 pp. 1144-1203.
- COSTA, U.R., FYFE, W.S., KERRICH, R. and NESBITT, H.W. 1980. Archean Hydrothermal Talc; Evidence for high Ocean Temperatures. Chemical Geology, 30, pp. 1144-1203.
- DAVIDSON, A., BRITTON, J.M., BELL, K. and BLENKINSOP, J. 1979. Regional Synthesis of the Grenville Province of Ontario and western Quebec. In Current Research, Part B, Geological Survey of Canada, Paper 79-1B, pp. 153-172.
- DICKSON, A.D. 1981. Canada Talc Industries (History - Henderson and Conley Mines to 1951, History from 1951). Unpublished Manuscript, Canada Talc Industries Ltd., Madoc, Ontario, 17 p.
- ENGEL, A.E.J. and WRIGHT, L.A. 1960. Talc and Soapstone. In Industrial Minerals and Rocks. Edited by J. L. Gillson, American Institute of Mining Engineers Inc., New York, 934 p.
- EVANS, M.E. 1926. Report on the Talc Mine of Asbestos Pulp Company of Madoc, Ontario, Unpublished Manuscript, 9 p.
- FORTUNÉ, J.P., GAVOILLE, B. and THIBAUT, J. 1980. Le gisement de talc de Trimouns pres Luzenac (Ariege): Publications du 26e Congres Geologique International, Paris, Gisements Francais, v. E10, p. 43.
- FRISCH, J.C. and HELGESON, H.C. 1984. Metasomatic phase relations in dolomites of the Adamello Alps. American Journal of Science, v. 284, pp. 121-185.
- FÜCHTBAUER, H. and GOLDSCHMIDT, H. 1963. Beobachtungen zur Tonmineral-Diagenese, Proc. of 1st International Clay Conference, Stockholm, pp. 99-111.
- GAUTHIER, M. 1982. Métallogénie du zinc dans la région de Maniwaki-Gracefield, Québec. Ph.D. Thèse, Ecole Polytechnique, Montréal, 209 p.
- GAUTHIER, M. 1981. Métallogénie du zinc dans la région de Maniwaki. Rapport Intérimaire DPV-753, Ministère de l'Energie et des Ressources, Québec, 24 p.

- GOLDBERG, E.J. and WEHRUNG, J.M. 1981. Analysis of two talc samples by SEM, EDXA. Consultant Report to W.R. Barnes Company Ltd., Waterdown, Ontario, 18 p.
- GUIARD, G. 1973. Sur la genèse des gisements métasomatiques de talc et de chlorite magnésienne des pyrénées et sur les relations entre le talc et la magnésite. In les Roches Plutoniques dans leurs rapports avec les gites minéraux. Edited by P. Morin. Masson et Cie, Paris, pp 369-395.
- HEWITT, D.F. 1957. Talc Deposit of Canada Talc Industries Limited, Madoc, Ontario. In The Geology of Canadian Industrial Mineral Deposits, Sixth Commonwealth Mining and Metallurgical Congress, pp. 240-243.
- HEWITT, D.F. 1964. Geological notes for maps nos. 2053 and 2054, Madoc-Ganonoque area. Ontario Department of Mines, Geological Circular 12, 33 p.
- HEWITT, D.F. 1968. Geology of Madoc Township and the north part of Huntingdon Township, Hastings County. Geological Report 73, Ontario Department of Mines, 45 p.
- JOHANNES, W. 1969. An experimental investigation of the system $MgO-SiO_2-H_2O-CO_2$. American Journal of Science, 267, pp. 1083-1104.
- KAY, G.M. 1942. Ottawa-Bonnechere Graben; Geological Society of America Bulletin, 53, 585 p.
- KERRICK, D.M. 1974. Review of Metamorphic Mixed-Volatile (H_2O-CO_2) Equilibria. American Mineralogist, 59, pp. 729-762.
- KROGH, T.E. and DAVIS, G.L. 1968. Geochronology of the Grenville Province: Carnegie Institute of Washington, Yearbook 67, pp. 224-230.
- LOGAN, W.E. 1864. On the Occurrence of Organic Remains in the Laurentian Rocks of Canada. American Journal of Science, 37, pp. 272-273.
- LONSDALE, P. 1978. Submersible exploration of Guaymas Basin: a preliminary report of the gulf of California 1977 operation of DSV-4 Seacliff. Scripps Institute of Oceanography, Woods Hole, Massachusetts, Ref. ser., 78-1, p. 16.
- LUMBERS, S.B. 1967. Geology and mineral deposits of the Bancroft-Madoc area. In Guidebook-geology of parts of eastern Ontario and western Quebec. Edited by S.E. Jenness. Geological Association of Canada, pp. 13-29.

- MERCOLLI, I. 1980. Fluor-Verteilung in Tremolit und Talc in den metamorphen Dolomiten des Campolungo (Tessin) und ihre phasen petrologische Bedeutung. Schweiz. mineral. petrolog. Mitt., 60, pp. 31-44.
- METZ, P. 1970. Experimentelle Untersuchung der Metamorphose von kieselig dolomitischen sedimenten. Contribution to Mineralogy and Petrology, 28, pp. 221-250.
- MILLER, W.G. and KNIGHT, C.W. 1913. The Precambrian Geology of South-eastern Ontario. Ontario Bureau of Mines, Annual Report, 22, part 2, 151 p.
- MOORE, J.M., Jr. and THOMPSON, P.H. 1972. The Flinton Group, Grenville Province, Eastern Ontario, Canada; In Precambrian Geology, Section 1, 24th International Geological Congress, Montreal, P.Q., Proceedings Sect. 1, pp. 221-229.
- MOORE, J.M., Jr. and THOMPSON, P.H. 1980. The Flinton Group: a late Precambrian metasedimentary succession in the Grenville Province of eastern Ontario. Canadian Journal of Earth Sciences, 17, pp. 1685-1707.
- OGDEN, D.G. 1981. Mineralogy of Canada Talc Industries Limited. Talc Ore as mined and processed at Madoc, Ontario (unpublished report). Canada Talc Industries Ltd., Madoc, Ontario, 4 p.
- OSBORNE, F.F. 1931. Non-metallic Mineral Resources of Hastings County, Ontario. Ontario Department of Mines. Annual Report XXXIX, part VI, pp. 22-59.
- RICE, J.M. and FERRY, J.M. 1982. Buffering, infiltration and the control of intensive variables during metamorphism. In Characterization of metamorphism through mineral equilibria. Edited by J. M. Ferry. Reviews in Mineralogy, 10, pp. 263-324.
- RICHARDSON, J.A. 1981. Cantal 325. Product data, Canada Talc Industries Ltd., Madoc, Ontario, 1 p.
- ROE, A.L. 1975. Talc and Pyrophyllite. In Industrial Minerals and Rocks (4th Edition). Edited by S.J. Lefond. American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., New York, 1360 p.
- ROSCOE, W.E., 1966. Structural control of a Talc Deposit near Madoc, Ontario. B.Sc. thesis, Queen's University, Ontario, 54 p.
- ROSENBERG, P.E. and HOLLAND, H.D. 1964. Calcite-Dolomite-Magnesite Stability Relations in Solutions at Elevated Temperatures, Science, v. 145, pp. 700-701.

- ROSENBERG, P.E. and MILLS, J.W. 1966. A Mechanism for the Replacement of Magnesite in Dolomite. *Economic Geology*, v. 61, pp. 582-586.
- SANDOMIRSKY, P. 1954. Geology of the Henderson and Conley Talc Mines, Madoc, Ontario. M.Sc. thesis. University of Western Ontario, London, Ontario, 128 p.
- SHIROZU, H. 1974. Geology of Kuroko Deposits. *Society of Mining Geologists of Japan, Mining Geology Special Issue* 6, pp. 1-9.
- SETHURAMAN, K. and MOORE, J.M., Jr. 1973. Petrology of metavolcanic rocks in the Bishops Corners-Donaldson area, Grenville Province, Ontario. *Canadian Journal of Earth Sciences*, 10, pp. 589-614.
- SILVER, L.T. and LUMBERS, S.B. 1966. Geochronological studies in the Bancroft-Madoc area of the Grenville Province, Ontario. *Geological Society of America, Special Publication* 87, p. 156.
- SLACK, J.F. 1982. Tourmaline in Appalachian-Caledonian massive sulphide deposits and its exploration significance, *Applied Earth Science, Transactions Section B. Institute of Mining and Metallurgy*, v. 91, pp. 81-89.
- SPENCE, H.S. 1922. Talc, Steatite and Soapstone. Mines Branch, Department of Mines, Ottawa, Publication No. 583.
- SPENCE, H.S. 1940. Talc, Steatite and Soapstone. Canada Department of Mines and Resources, Mines and Geology Branch, No. 803, part 1.
- TARR, W.A. and KELLER, W.O. 1940. Chert in the Grenville Marble, Ross Township, Renfrew County, Ontario. *Journal of Geology*, 48, pp. 196-204.
- TILLEY, C.E. 1948. Earlier stages in the metamorphism of siliceous dolomites. *Mineralogical Magazine*, 28, pp. 272-276.
- THOMPSON, P.H. 1972. Stratigraphy, Structure, and Metamorphism of the Flinton Group in Bishops Corners, Madoc area. Grenville Province, eastern Ontario. Ph.D. thesis, Carleton University, Ottawa, Ont., 268. p.
- VALDIA, K.S. 1968. Origin of the Magnesite Deposits of Southern Pithoragarh, Kumaun Himalaya, India. *Economic Geology*, 63, pp. 924-934.
- WILSON, M.E. 1926. Talc deposits of Canada: Geological Survey of Canada Economic Geology, Series, No. 2.
- WILSON, M.E. 1929. Fluorspar deposits of Canada: Geological Survey of Canada, Economic Geology Series, No. 6.

- WINKLER, H.G.F. 1979. Petrogenesis of metamorphic rocks (5th Edition). Springer-Verlag, New York, 348 p.
- WOLLAST, R., MACKENZIE, F.T. and BRICKER, D.P. 1968. Experimental precipitation and genesis of sepiolite at earth-surface conditions. *American Mineralogist*, 53, pp. 1645-1662.
- WYNNE-EDWARDS, H.R. 1972. The Grenville Province. In *Variations in tectonic styles in Canada*. Edited by R.A. Price and R.J.W. Douglas. Geological Association of Canada, Special Paper 11, pp. 263-334.
- ZIERENBERG, R.A., SHANKS, W.C. 1983. Mineralogy and Geochemistry of Epigenetic Features in Metalliferous Sediments, Atlantis II, Deep. Red. Sea. *Economic Geology*, 78, pp. 57-72.
- ZWART, H.J. 1953. La geologie du massif du Saint-Arthelemy: Leidse Geologische Mededelingen, 18, 228 p.

APPENDIX I

Field and Laboratory Investigations

The present study concentrated on three areas:

- a) geological mapping and core logging
- b) laboratory investigations
- c) literature search.

The third point does not need to be described. The field and laboratory investigations are described below.

Field methods

The field investigations were largest component of this work. They were initiated in June 1981 and were completed in May 1982.

The fieldwork may be subdivided into three major components:

- a) underground mapping
- b) surface mapping
- c) core logging.

Underground mapping

The washing of the back and walls of the drifts was necessary, because a 2 to 3 mm thick layer of dust and mud covered the back and the walls of the workings. Underground mapping took place during the summer months of 1981.

Accurate base maps were provided by Canada Talc Industries Ltd. The 541 foot level (portion of this level was previously mapped by Roscoe 1966) and new decline were mapped on a scale of 1:360. The chain and carpenters rule were the most useful

instruments, since significant changes in magnetic field caused by power lines, transformers, rails and pipes made the use of the compass inaccurate in most of the mine workings. The New Conley third level workings were partly mapped in May 1982.

Surface mapping

The surface mapping was done through the autumn of 1981. The outcrops were located mainly by careful compass bearings and chaining. Excellent enlargements of aerial photographs of the area were available as well as a good base map on scale of 1:1200.

Diamond drilling

Diamond drilling was initiated by Canada Talc Industries Ltd. late in 1981 and completed in May 1982. This diamond drilling was responsible for the discovery of the East deposit and also contributed to the knowledge of the stratigraphy in the vicinity of the East deposit.

The locations and elevation of some boreholes were accurately determined by transit, but most boreholes represented on figure were located by chain and compass bearings.

Laboratory investigations

Laboratory work consisted of two components:

- a) petrological investigations
- b) geochemical investigations.

Petrological investigations

Over fifty thin sections and polished sections of the talc horizon and host rock units in the mapped area were examined using a polarizing microscope.

This work was fortified by X-ray diffraction and to a limited extent by qualitative microprobe analysis and mineral staining. This work was performed mainly during March, May and June of 1982.

In addition SEM and EDXA studies on two coarse flaky talc specimens by Goldberg and Wehrung (1981), X-ray diffraction studies of Blount (1982) and Hicks (1982) were incorporated.

These three latest studies were ordered and financed by Canada Talc Industries Ltd.

Geochemical Investigations

The geochemical study consisted of analysis of the major elements. Ten samples of the host rock and talc were submitted to Centre de Recherche Minérale, Sainte-Foy, Québec. Concentrations of SiO_2 , MgO , CaO , Na_2O , K_2O , TiO_2 and MnO were determined by Atomic Absorption Spectrometry (AAS). P_2O_5 was determined by colorimetry. Sulphur was determined by combustion in the induction furnace followed by infrared detection. Precision of the individual analysis is equivalent to a total 98-102%.

APPENDIX II

Orientation of the Madoc and Queensborough Synclines

The stereographic projections of the Queensborough and Madoc synclines were produced in order to estimate orientation of these major structures.

The data used for the construction was compiled from Hewitt's (1968) map. Poles of the beddings were used in both cases.

Madoc syncline

The plot of poles of the bedding planes from the Madoc area is an equiangular projection. It is based on eight measures only, and therefore it is highly speculative. At least two concentrations of the poles (along two distinct great circles) may be recognized. It suggests that at least two periods of deformation affected the area. If one is forced to speculate on the orientation of the Madoc syncline based on the above described projection, it may be said that the syncline plunge steeply to the East (50° or more towards $N16^{\circ}E$) as indicated by a black dot (fig. IIa)

Queensborough syncline

The equal area stereographic projection from the Queensborough syncline is based on 30 orientation measurements of the bedding planes. Nearly peripheral dispersion pattern of the poles of bedding planes suggests that "type I interference pattern" of Ramsey (1967) is predominant in the area.

Fig. 11a - Madoc syncline poles of the bedding planes.
(x = poles of the bedding planes, - = fold axis)

Fig. 11b - Queensborough syncline (poles of the bedding planes
contoured, N = 30). Peripheral dispersion pattern of poles of
bedding planes.

The variability in the plunges of the poles of the bedding that axes of F_1 (folds related to D_1) are affected by subsequent deformations . Black dots indicate the plunge ($80^\circ \longrightarrow N254^\circ E$), of the axis (fig .I Ib)

N.B. It is impossible to determine from these diagrams, if two or more major periods of folding affected the area. Tectonic style of the area is described in the main text.

APPENDIX III

Descriptions of Thin Sections

Abbreviations used in thin section descriptions

ak	actinolite	pl	phlogopite
ap	apatite	pg	plagioclase
ab	albite	py	pyrite
bi	biotite	po	pyrrhotite
ca	calcite	q	quartz
cb	carbonate	ru	rutile
ch	chlorite	sup	serpentine
do	dolomite	sc	silica
di	diopside	sp	sphalerite
gf	graphite	ti	sphene
hem	hematite	s	sulphides
h	hornblende	tk	talc
mi	mica	tl	tourmaline
mu	muscovite	tr	tremolite
op	opaques	vm	vermiculite
or	orthoclase	Zo	zoisite

Major minerals (>5%) are listed in front of the oblique; minor and accessory minerals are listed after the oblique.

() not positively identified

A → B mineral A alters to mineral B

Thin section #	Rock type	Mineralogy	Minerals in contact	Textures and Remarks
R-81-110A	Flaky talc	tk, do	tk-do	talc (1 cm long) flakes; ta-pseudomorph after tr (?)
R-81-116a	Flaky talc	tk, do	tk-do,	medium grain size, tk pseudo- morphs after tr
R-81-116b	steatite	tk, tr, ca/(q), s	-	tk most abundant replacing tr, Ca is very fine, pervasive
R-81-116c	steatite	tr, tk, (do)	-	tr alters to ta
R-81-116d	steatite	tk, do, (tr)	tk-do	tk pseudomorph after tr; remnants of do
R-81-51	steatite	tk, sup, dol (tr)	tk-do-(sup) tr-ta	very fine-grained talc mass
R-81-52	steatite	tk, tr, ca, s/op	tr-ta	v.f.g. to mass, s disseminated or as laminations, ca fracture filling
R-81-121	steatite	tk, tr/q(z)		very fine grain to massive
R-81-126	steatite	tk, sup/(s)	-	laminations
R-81-133	steatite	tr, sup, do	tr-sup-do	v.f.g.
R-81-135	steatite (with dolomite phe- nocryst)	sup, tk,	tk-sup	v.f.g. (phenocryst = 1 cm across

Thin section #	Rock type	Mineralogy	Minerals in contact	Textures and Remarks
R-81-138	partially steatized	tr, do, sup(ta)		very fine grain
R-81-110	coarse talc-tremolitic, micaceous dolomitic marble contact	mu, do, tr, /s	mu-tr-do	lenses of dolomite are preserved
R-81-50	tremolitic micaceous dolomitic marble (5 feet from the talc contact)	cb, tr/mu, op		
R-81-112	tremolitic micaceous dolomitic marble	cb, tr/mu, op (ap)	q-tr-ca	cloudy, quartz strongly altered mica, tremblite alters to talc
R-81-120	tremolitic micaceous dolomitic marble (brown laminated)	do, tr, mu/ta		
R-81-120A	tremolitic micaceous dolomitic marble	do, tr, mu/(ta) ca(di)		
R-81-129	tremolitic micaceous dolomitic marble	do, a, tr/ta, m		

Thin section #	Rock type	Mineralogy	Minerals in contact	Textures and Remarks
R-81-130	tremolitic mica- ceous dolomitic marble (light amber mica on	ca, ak, t, ta/pl	ca, tr, mu	tremolite unaltered
R-81-131	muscovite bearing tremolitic marble	tr, do/ta, ca, mt (di)	tk-ca ca-q-tr	section rims around quartz; tremolite is unaltered; actinolite is altered
R-81-132	sphalerite bearing marble	tr, do/mu, sp, py, ca		talc and calcite as pervasive alteration
R-81-136	stringer of serpentinized do- lomite in tremo- lite micaceous marble	do, sup, (tl)		
R-81-137	tremolitic, mica- ceous marble (5 cm block altered on the surface)	tr, tk, (do)	tr-mu (do)	fractured, % of tremolite increasing away from fracture
R-81-139	tremolitic mica- ceous marble (footwall)	tr, ca, mt/ti (zo), (op)	tr-ca	

Thin section #	Rock Type	Mineralogy	Minerals in contact	Textures and Remarks
R-81-115 X-ray (diopside?)	tremolitic mica- ceous marble (transition zone)	do, tr, mu, py		dolomite alters to talc very fine grain
CT-82-1 (299f)	tr rich marble	th, tr/(ak), sp	tk-tr	two generations of amphi- boles. Talc in pseudo- morphs after first gene- ration of amphibole (tremolite)
CT-82-3 (209f)	light green tre- molitic marble with translucent silica band	q, tr, mi/ta, ca	q-tr-(mi) ca-tr	fresh angular quartz mosaic with some tremo- lite and mica. Talc developed in the shear zone
R-81-119	quartzite	q, tr, ca, do tk, tr/op	q, tk, ca q, tr, tk	stromatolitic texture
R-81-122	quartzite	q, tk, ca/do	tk, tr, q q, tr, ca	stromatolitic texture
R-81-22	mottled blue marble	do-tr-ca	tr-do	coarse tremolite within light zone, fine tremo- lite within dark zone
R-81-123	mottled blue marble	do-tk		talc in fractures only No tremolite phenocrysts
EX-81-20	"phyllite" (massive)	tr, ta, (mi), ch		

Thin section #	Rock Type	Mineralogy	Minerals in contact	Textures and Remarks
CT-82-5 (48f)	"phyllite"	ca, ak, ta/tr	tk-tr-act-ca ca-ta-tr	tremolite altering to talc and calcite. Talc and tremolite bands alternating with calcite rich bands
R-81-125	fault gauge	pl, ca, py/s, tl, q	pl-ca-q-tl	py $\leq$ 2 mm
R-81-127	tourmaline bearing chert (from the tremolitic mica-ceous marble)	q, tr, tl/s, do (ap)	tr-q-(tk)? q-ca-tr	tr $\rightarrow$ tk tl as phenocrysts with abundant tr inclusion.
Ex-81-21	Metasomatic tremolitic vein (3 cm thick)	tr, ca/s(?), op	tr-ca	Prismatic tremolite phenocrysts perpendicular to vein walls. Sulphides are concentrated near the vein contacts.
CT-82-3	aphanitic tremolitic hard and brittle light green rock	q, tr, tk/mica	q-tr	rich bands contain some mica flakes and minute tremolitic crystals
Tc3-81-1	tourmaline bearing tremolitic band	tl, tr/s		talc phenocrysts, sulphides concentrates on the boundary of tourmaline

Thin section #	Rock Type	Mineralogy	Minerals in contact	Textures and Remarks
CT-82-3 (251)	aphanitic massive light green silicified marble	q, tr	q-tr	no rims, quartz rich, with minute prismatic tremolite crystals.
R-81-111	marble near a fault	tr, tl, do/s, ap, q.		laminated, tremolite occurring in bands
R-81-124	amphibolite dyke dark green, cut by calcite vein	ca, hb, q/pg, pl, s op		ab and pl phenocrysts. ca phenocrysts in cal- cite vein which is young- er than hb bearing dyke
CT-82-2 (255)	fractures filled by talc ("New Conley" talc)	do-tr-ta/(q)	tk-do	talc occurs mainly in fractures but also as clusters with dolo- mite
R-81-104	marble altered by amphibolite dyke (2 cm from contact)	ca, tr, tk/ak	ca-tr- tk	two generation of amphi- bole actinolite - early tremolite - later
CON-82-2	marble	sup, tr/ca	Sup-ca-tr	aphanitic, massive, greenish, laminated
CON-82-3	marble	sup, ca, do/mu and ta	Sup-ca-do	laminated, aphanitic, purplish and greenish

Thin section #	Rock Type	Mineralogy	Minerals in contact	Textures and Remarks
EX-81-6	greenstone	ca, ch, ml, pg. (q)		strongly chloritized green and light beige laminations 1 cm thick Biotite alters to chlo- rite
EX-81-8	Paleozoic cover (greenish variety)	ca, q, op		strongly cloudy thin section
EX-81-18		tl, tr, q, ca, ch hem: py		strongly altered
EX-81-3	granite for granitized sediment)	or, q, ch/he, (bl)		biotite altering to chlorite
CT-81-1 (322f)	metapelite	ca, pl, q/py unknown high relief accessory		shistose

APPENDIX IV

Detailed Morphology of the Henderson Deposit

The morphology of the Henderson deposit was described in the main text. Detailed cross sections presented in this appendix are conveniently located on the geologic maps of the decline and Henderson deposit (3rd level). Cross sections are looking SW and are at 100 feet intervals. Elevations indicated on the cross sections are related to the bench mark on the collar of the "Old" Henderson shaft, which is estimated to be 1200 feet above sea level. Maps and cross sections have a common legend which is presented on the next page.

Legend

Lithology

- 9 dykes
- 8 undifferentiated marble
- 7 stromatolitic dolomitic quartzite
- 6 "mottled blue" marble
- 5 tremolitic micaceous dolomitic marble (hanging wall)
- 4 talc ore (4a steatite, 4b coarse flaky ore)
- 3 partly steatized tremolitic micaceous dolomitic marble*
- 2 tremolitic micaceous dolomitic marble (footwall)
- 1 "Phyllite"

* important from the engineering and economic view points.

Other symbols

▣ Winze or shaft

fold plunging 10°

excavation

geological contacts

3 of/de 3

METZ

LEGEND

- TREE LINE
- IRON PIN
- ALL WEATHER ROAD
- ROAD
- TRAIL
- HOUSE FOUNDATION
- BUILDING
- RAIL FENCE
- STREAM OR DITCH
- SWAMP
- LAKE SHORE LINE
- SHARP DROP IN ELEVATION
- TEST PIT
- SHAFT
- TRENCH
- HORIZONTAL PROJECTION OF THE BOREHOLE DRILLED FROM THE SURFACE

LEGEND

DYKES AND SILLS

a) CALCITE-PHLOGOPITE-QUARTZ-SULPHIDE VEIN, b) amphibolite

c) mica-pyrite-tourmaline

d) SULPHIDE-BEARING VEIN OF SILICEOUS APPEARANCE:

SILICEOUS MARKER

UNSUBDIVIDED MARBLE

STROMATOLITIC QUARTZITE

MOTTLED-BLUE MARBLE

TREMOLITIC, MICACEOUS, DOLOMITIC
MARBLE (HANGING WALL)

TALC-BEARING HORIZON

TREMOLITIC, MICACEOUS, DOLOMITIC
MARBLE (FOOTWALL)

PHYLLITE (CONTAINS BLACK TALC)

TREMOLITIC, MICACEOUS, DOLOMITIC
MARBLE (HANGING WALL)

ND

- ☐ DYKES AND SILLS
- ☐ PYRITE-QUARTZ-SULPHIDE VEIN, b) amphibolite
- ☐ c) mica-pyrite-tourmaline
- ☐ VEIN-BEARING VEIN OF SILICEOUS APPEARANCE
- ☐ SILICEOUS MARKER
- ☐ UNSUBDIVIDED MARBLE
- ☐ STROMATOLITIC QUARTZITE
- ☐ MOTTLED-BLUE MARBLE
- ☐ TREMOLITIC, MICACEOUS, DOLOMITIC MARBLE (HANGING WALL)
- ☐ TALC-BEARING HORIZON
- ☐ TREMOLITIC, MICACEOUS, DOLOMITIC MARBLE (FOOTWALL)
- ☐ PHYLLITE (CONTAINS BLACK TALC)
- ☐ TREMOLITIC, MICACEOUS, DOLOMITIC MARBLE (HANGING WALL)

THE BOREHOLE DRILLED FROM THE SURFACE

TEST PIT

SHAFT

TRENCH

HORIZONTAL PROJECTION OF THE BOREHOLE DRILLED FROM THE SURFACE

HORIZONTAL PROJECTION OF UNDERGROUND BOREHOLE

UNDERGROUND MINE WORKINGS
 a) 3rd LEVEL, HENDERSON
 b) RAMP
 c) 3rd LEVEL, OLD CONLEY

LEGEND

UNCONSOLIDATED PLEISTOCENE DEPOSITS AND
 FLAT LYING CAMBRO-ORDOVICIAN ROCKS
 ARE NOT SHOWN

- UNCONFORMITY
- TOURMALINE BEARING DYKES
- AMPHIBOLITE
- GRANITOID ROCKS
- INTRUSIVE CONTACT
- SILICEOUS MARKER
- UNDIFFERENTIATED MARBLE
- STROMATOLITIC MARBLE
- MOTTLED BLUE MARBLE

100

4

9

2

10

SURVEY STATION

MARBLE (FOOTWALL)

PHYLITE (CONTAINS BLACK TALC)

TREMOLITIC, MICACEOUS, DOLOMITIC

MARBLE (HANGING WALL)

TALC BEARING HORIZON

TREMOLITIC, MICACEOUS, DOLOMITIC

MARBLE (FOOTWALL)

PHYLITE (CONTAINS BLACK TALC)

LOGICAL CONTACTS

DUDE OF LAYERING

S, SHEARS (defined, assumed)

KEY STATION

GEOLOGICAL SYMBOLS	
	GEOLOGICAL BOUNDARY (defined, approximate, assumed)
	BEDDING (inclined, vertical)
	FOLIATION (inclined, vertical)
	JOINT (inclined, vertical)
	MULTIPLE FOLD (plunge unknown, arrow indicates plunge, dot indicates subvertical plunge)
	ANTICLINE (plunge unknown, arrow indicates plunge, dot indicates subvertical plunge)
	SYNCLINE (plunge unknown, arrow indicates plunge, dot indicates subvertical plunge)

- 8 MOTTLED BLUE MARBLE
- TOURMALINE ZONE
- 12 GRANITOID ROCKS
- INTRUSIVE CONTACT ---
- 11 SILICEOUS MARKER
- 10 UNDIFFERENTIATED MARBLE
- 9 STROMATOLITIC MARBLE
- 8 MOTTLED BLUE MARBLE
- TOURMALINE ZONE
- 6 TALC ZONE
- 5 PHYLLITE
- 4 4a 4) TREMOLITIC, MICACEOUS, DOLOMITIC MARBLE
4a) IS MORE SILICEOUS THAN 4)
- 3 FELDSPAR PORPHYRY
- 2 METAPELITE
- 1 METAVOLCANICS AND METASEDIMENTS
OF VOLCANIC ORIGIN

THE STRATIGRAPHIC RELATIONSHIP OF THE MAYO GROUP,
IN WHICH METASEDIMENTARY ROCKS OVERLIE THE
METAVOLCANICS WAS APPLIED IN CONSTRUCTION OF
THIS SEQUENCE.

TALC DEPOSITS
OF PART OF LOTS 14 and 15
CONCESSION 14

TOWNSHIP OF HUNTINGDON

N

dot indicates subvertical plunge

SYNCLINE (plunge unknown, arrow indicates plunge,
dot indicates subvertical plunge)

LAKE

GEOLOGICAL SYMBOLS

	GEOLOGICAL BOUNDARY (defined, approximate, assumed)
	BEDDING (inclined, vertical)
	FOLIATION (inclined, vertical)
	JOINT (inclined, vertical)
	MULTIPLE FOLD (plunge unknown, arrow indicates plunge, dot indicates subvertical plunge)
	ANTICLINE (plunge unknown, arrow indicates plunge, dot indicates subvertical plunge)
	SYNCLINE (plunge unknown, arrow indicates plunge, dot indicates subvertical plunge)
	FAULT (indicated by drilling)
	BRECCIATED ZONE
	OUTCROPS, AREA OF OUTCROP

SCALE

TOWNSHIP OF HUNTINGDON

SCALE

THE STRATIGRAPHIC RELATIONSHIP OF THE MAYO GROUP,
IN WHICH METASEDIMENTARY ROCKS OVERLIE THE
METAVOLCANICS WAS APPLIED IN CONSTRUCTION OF
THIS SEQUENCE.

TALC DEPOSITS
OF PART OF LOTS 14 and 15
CONCESSION 14

TOWNSHIP OF HUNTINGDON
COUNTY OF HASTINGS

fig.6

G.J.S. 1982

SCALE
100 0 100 200 300 FEET

80 0 80 METERS

CANADA TALC I
DECLA
PRELIMINARY GH
HENDERSON
fig.
SEPTEMBER 18/1981

8800N

8800N

8700N

CANADA TALC INDUSTRIES LTD.

DECLINE

PRELIMINARY GEOLOGICAL MAP

HENDERSON DEPOSIT

fig. 8

SEPTEMBER 18 / 1981

G. I. SIMANDL

SCALE

LEGEND

DYKES AND SILLS

- a) CALCITE-PHLOGOPITE-QUARTZ-SULPHIDE VEIN
- b) AMPHIBOLITE c) mica-pyrite-tourmaline
- d) SULPHIDE-BEARING VEIN OF SILICEOUS APPEARANCE

SILICEOUS MARKER

UNSUBDIVIDED MARBLE

STROMATOLITIC QUARTZITE

MOTTLED-BLUE MARBLE

TREMOLITIC, MICACEOUS, DOLOMITIC
MARBLE (HANGING WALL)

TALC BEARING HORIZON

TREMOLITIC, MICACEOUS, DOLOMITIC
MARBLE (FOOTWALL)

PHYLLITE (CONTAINS BLACK TALC)

GEOLOGICAL CONTACT (DEFINED, ASSUMED)

ATTITUDE OF LAYERING

FAULTS, SHEARS (DEFINED, ASSUMED)

SURVEY STATION • 345

LEGEND

- a) CALCITE-
- b) AMPHIBOLITE
- d) SULPHIDE

GEOLOGICAL CO

ATTITUDE OF LA

FAULTS, SHEARS

SURVEY STATION

TO CONLEY
SHAFT

36

317

3

328

320

320

LEGEND

DYKES AND SILLS

a) CALCITE-PHLOGOPITE-QUARTZ-SULPHIDE VEIN

b) AMPHIBOLITE c) mica-pyrite-tourmaline

d) SULPHIDE-BEARING VEIN OF SILICEOUS APPEARANCE

SILICEOUS MARKER

UNSUBDIVIDED MARBLE

STROMATOLITIC QUARTZITE

MOTTLED-BLUE MARBLE

TREMOLITIC, MICACEOUS, DOLOMITIC
MARBLE (HANGING WALL)

TALC BEARING HORIZON

TREMOLITIC, MICACEOUS, DOLOMITIC
MARBLE (FOOTWALL)

PHYLLITE (CONTAINS BLACK TALC

GEOLOGICAL CONTACT (DEFINED, ASSUMED)

ATTITUDE OF LAYERING

FAULTS, SHEARS (DEFINED, ASSUMED)

SURVEY STATION

TO COMLEY
SHAFT

316

317

318

6

320

323

FAULTS, SHEARS (DEFINED, ASSUMED)

SURVEY STATION #345

FAULTS, SHEARS (D

SURVEY STATION

8700N

8700N

HENDERSON SHALE

HENDERSON SI

337

339

337

FAULTS, SHEARS (DEFINED, ASSUMED)

SURVEY STATION #346

CANADA TALC INDUSTRIES LTD.

THIRD LEVEL

PRELIMINARY GEOLOGICAL MAP

HENDERSON DEPOSIT

SEPTEMBER 18 / 1981

fig.11

G.I. SIMANDI

SCALE

30 0 30 60 feet

0 5 10 15 20 25m

8500N

9000E

9500E

10000E

10500E

10500E

CANADA TALC INDUSTRIES LTD.

THIRD LEVEL

PRELIMINARY GEOLOGICAL MAP

HENDERSON DEPOSIT

SEPTEMBER 18/1981

fig.11

G. E. SIMANDI

SCALE

29000 E

30000 E

40000 E

40200 E

40300 E

LTD.

G. E. SIMANDI

END

05.01.88

FIN