Regional Porosity Evaluation Of The Catoche Dolomite, St. George Group, Onshore Western Newfoundland.

George S. Langdon
Centre for Earth Resources Research
Memorial University of Newfoundland
St. John's, Newfoundland
February 6, 1992

EL# 92-103-01-EG
Release Date: December 31, 1997

Introduction and Methods

This project to study the porosity within the dolomites of the Catoche Formation, western Newfoundland combines a field and an off ice-based component. The project was initiated in mid-September, 1991, and 12 days were spent in the field in October, 1991. The field excursion enabled the collection of about 75 samples, mostly from the Catoche Formation, but a few from dolomitized carbonates within other formations of the St. George Group. These rocks were slabbed and thin sections were made from 64 of them.

Thin sections were examined and described in terms of the lithological breakdown of Haywick (1985), described later in this report. Dolostones and dolomitic limestones with other than very minor porosity (<1%) were point-counted for an accurate determination of porosity. Exceptions were the Cape St. George (CSG) and Cape Cormorant (CC) samples which were received only a short time before the project deadline: porosity in these was estimated visually from thin section.

In setting up the field portion of the project, communications were made with the following current and former west coast workers: R. K. Stevens, N. P. James, B. R. Pratt, I. Knight, T. E. Lane and W. D. Boyce. H. G. Machel was contacted for references regarding fluid flow and dolomitization. In the late stages of the project T. E. Lane helped immensely with discussions of fluid flow, tectonics, dolomitization, and porosity development. These people are thanked for their advice.

The following symbols and abbreviations have been used in this report:

Samples and Localities

CC	Cape Cormorant
CSG	Cape St. George
TM	Table Mountian (Smelt Canyon)
TMN	Table Mountain North
IB	Isthmus Bay
A	Aguathuna
SC	Ship Cove
M	Mainland
LC	Lower Cove
TP	Table Point
PC	Port au Choix
DH	Daniel's Harbour

General Abbreviations

GNP	Great Northern Peninsula
P au P	Port au Port Peninsula

Haywick Lithologies

DL	Dololaminite
MA	Matrix dolomite
MO	Mottle dolomite
PA	Pervasive-A dolomite
PB	Pervasive-B dolomite
SA	Saddle dolomite

Geological Map Units

TP	Table Point Fm.
TC	Table Cove Fm.
AG	Aguathuna Fm.
Cd	Catoche dolomite
C1	Catoche Limestone
MS	Mainland Sandstone
CC	Cape Cormorant Fm.
CA	Catoche Fm.
BH	Boat Harbour
SH	Shale of Humber Arm Allochthon
WB	Winterhouse Brook Fm (Long Point Gp.)
L	Lourdes Fm.
CB	Clam Bank Gp.

Stratigraphy Of The St. George Group

The following review of the stratigraphy is based upon Knight and James (1987).

The study area in western Newfoundland (Figure 10, Maps 1-4, following page) contains a thick sequence of sedimentary rocks which developed along the ancient continental margin of North America during the Lower Paleozoic. These sediments can be divided into four sequences (Knight, 1980):

1. The lower Cambrian Labrador Group, comprising rift facies volcanics and clastics associated with the birth of Iapetus
2. the mid- to upper Cambrian clastics known as the Port au Port Group
3. the lower Ordovician St. George Group: shallow water limestones and dolomites
4. the middle Ordovician Table Head Group, mainly shallow water limestones which pass upward into shales

These rocks outcrop in a 400 km belt which skirts the margins of the Humber Arm Allochthon and the Long Range Massif. Two of the best areas of exposure are the Port au Port Peninsula and area, where the rocks have been subjected to Acadian and Carboniferous faulting, and the eastern side of the Northern Peninsula, between Table Point and Cape Norman, where the strata are virtually flat- lying.

The St. George Group has recently been redefined by Knight and James (1987) to include only the early Ordovician limestone and dolostone section, which distinguishes them from the more siliciclastic , less fossiliferous carbonates of the late Cambrian Port au Port Group, and the distinctive massive limestones and shales of the mid-Ordovician Table Head Group. The new Group includes four formations: the Watt's

Bight, the Boat Harbour, the Catoche and the Aguathuna Formations. Their lithologies are summarized in Figure 1 (pdf - 209kb). In general, these formations reflect accretion of the early Ordovician continental shelf, and respectively represent an alternating succession of subtidal- peritidal-subtidal-peritidal carbonate sediments.

Knight and James describe the St. George Group as a succession of limestones and dolostones, with varieties in between these compositions, which were deposited in subtidal and peritidal environments. Subtidal rocks are characterized by well-bedded, bioturbated, fossiliferous mudstone to packstone with grainstone lenses or layers, and cryptalgal boundstone mounds. Peritidal lithologies include the above types plus a variety of muddy and grainy carbonates in repetitive, shallowing-upward sequences (James, 1984). These other lithologies include "parted, flaser- bedded, bioturbated, and fossiliferous lime and dolomite mudstone to packstone, with ripple-marked, skeletal, intraclastic, and rarely oolitic grainstone, and mud-cracked, laminated, dolomitic lime mudstone, dolostone or dolomitic shale" (Knight and James, 1987, p. 1930).

Detailed Stratigraphy
The Catoche Formation consists of well-bedded, fossiliferous, bioturbated gray limestones; compositionally they are mudstones to packstones, with abundant, frequently ripple-marked, intraclastic bioclastic grainstone lenses and thin beds. These lithologies are summarized in Figure 2 (pdf - 318kb). Common features of these rocks are abundant, often dolomitized trace fossils, and variably distributed boundstone mounds, which are composed of thrombolites, sponges, calcareous algae, and rare coral associated with large cephalopods, gastropods and trilobites. Mound sequences are best developed in the Pistolet Bay and Hare Bay areas. Other textural varieties include crossbedded, intraclastic rudstone, which occurs throughout the lower 12 m of the formation, and the Costa Bay Member, a peloidal limestone, which forms the upper 8 - 16 m of the formation in the Port au Port and eastern Northern Peninsula outcrop areas.

A ubiquitous and important feature of the Catoche Formation is its dolomitization. In the north, at Boat Harbour and Cape Norman (Figure 10) , it affects the lower part of the formation, in the east, at Canada Bay and Hare Bay, the middle part is affected, and at the Port au Choix type area and in the south, the upper 30-50 m of the formation is affected. These dolomites have been studied by Collins and Smith (1975), Haywick (1984), Haywick and James (1984), and Lane (1990) ; they have attracted attention for a long time because they are often rich in secondary porosity. Several types of dolomites and dolomitization are found, ranging from selectively dolomitized burrows in limestone, to more pervasive types, as well as the spectacular coarsely crystalline white saddle dolomite, which is associated with economic zinc mineralization at Daniel's Harbour. Dolomitization will be discussed in detail here in a later chapter.

The Catoche Formation is highly fossiliferous, with assemblages of trilobites (Fortey, 1979; Boyce, 1979, 1985), gastropods, cephalopods, ostracods, sponges, corals, pelmatazoan echinoderms, calcareous algae, graptolites, brachiopods and conodonts. Studies in trilobites (Fortey, 1979), conodonts (Stouge, 1982) and graptolites (Cumming, 1987; Boyce, 1985; Williams et al. , 1987) have established that the Catoche Formation is late Canadian (Cassinian) in age.

Paleogeography
The Catoche Formation was deposited as a package of dominantly open shelf subtidal limestones. The lower part of the formation represents shallow, peritidal settings, indicated by channel-bound and storm-generated intraclastic rudstones, tidal flat parted limestones and mud-cracked, laminated lime mudstones, and subtidal small sponge-thrombolite mounds (Knight and James, 1987, p 1941). Most of the formation, however, was deposited in an open subtidal shelf setting, characterized by bioturbated stratified limestone rich in a diverse benthonic fauna. The effect of high energy currents and waves is witnessed by grainstones and crosscutting surfaces. On other areas of the broad shelf cryptalgal sponge-rare coral boundstone mounds developed; these mounds proliferated on the eastern outboard part of the shelf, where they may have formed a prominent, high energy barrier facies. Such rocks are now exposed in Canada and Hare Bays.

The entire shelf gradually shallowed upward as deposition began to outpace relative subsidence; this is indicated by more restrictive faunas, fenestral limestones, cyclicity, and a transition to the peritidal conditions of the Aguathuna Formation.

Megacycles

Knight and James considered the stratigraphy of the St. George Group as two unconformity-bounded megacycles, characterized by the following general sequence of deposition: (1) basal peritidal sediments, (2) middle subtidal facies, (3) upper peritidal deposits (Figure 3 (pdf - 142kb)). The lower megacycle is composed of the Watt's Bight and most of the Boat Harbour Formations, and terminates at an unconformity near the top of the Boat Harbour; thus it was deposited during the Gasconadian and Deningian North American stages.

The upper megacycle includes the remainder of the Boat Harbour Formation, and the Catoche and Aguathuna Formations, and represents the latest Jeffersonian and entire Cassinian stages. The lower peritidal sediments of the megacycle includes the Barbace Cave member of the Boat Harbour Formation, and the basal 12 - 15 m of the Catoche Formation. These contain mostly low energy sediments such as burrowed mudstone to packstone deposited in quiet, shallow subtidal and adjacent intertidal environments. This succession is thicker on the Port au Port Peninsula (36m) than on the Northern Peninsula (12-23m).

The sediments of the middle subtidal part of the cycle include the next 90m to the top of the Catoche Formation; these are carbonate muds with numerous storm-generated sand lenses, which host a burrowing and diverse shelly benthonic fauna. The shelf st this time contained large bank complexes of thrombolites, clacareous algae, sponges, primitive corals, pelmatozoans and large shelly faunas. In the eastern outboard areas, such as Hare Bay, Pistolet Bay and Canada Bay, these appear to have formed a major mound barrier complex. These sediments represent a period when relative sea level rise equaled or exceeded the rate of carbonate sediment production.

The upper peritidal part of the megacycle is represented by the Aguathuna Formation; these microcrystalliine dolostones with, minor dolomitic shales and limestones were deposited as a system of shifting tidal flat islands accreting vertically and laterally on a very shallow shelf. The megacycle is terminated by an erosional disconformity at the top of the formation in the Port au Port area; on the Northern Peninsula significant breaks occur within the Aguathuna, and it most likely occurs within 15 m of the base of the formation in the Port au Choix and Daniel's Harbour areas (Knight, 1985a).

From a comparison with coeval sequences in other areas of the Appalachian and Caledonides, particularly in New York, Vermont, and the Mingan Islands (Quebec), it seems that the general stratigraphy compares very closely with that of the St. George, and furthermore, that a mid-Canadian transgression was an important deepening episode in the platform development of these areas (Figure 4 (pdf - 278kb)). These broadly developed megacycles, then, are related to the combination of eustatic sea level fluctuations and local subsidence controlled by regional tectonics. The St. George megacycles can be explained by sea level change, either as a result of glacioeustatic control (Fortey, 1984) or by a long-period rise and fall of sea level superimposed on slow platform subsidence (James, 1984). However, local tectonics must also be considered; the continental margin was a convergent, tectonically-influenced one by early Ordovician time, and the effect of tectonics is clearly seen in thickness variations and faulting which affect the Aguathuna Formation.

The recognition of megacycles is also a very useful concept in any discussion of the diagenetic dolomite. In general, these dolomites are located at the transition between the transgressive to regressive stage of the cycles, or may locally replace the total transgressive stage, as in the lower St. George megacycle, where basal transgressive deposits of the Watt's Bight Formation were completely replaced to produce a pervasive, non-porous dolomite (Knight, 1980b) . In the upper megacycle, well-developed diagenetic dolomites are thick and extensive in the western inner shelf area (Cape Norman), thinner in the southern (Port au Port) region, and in the Port au Choix to Daniel's Harbour area coexist with pseudobreccia-type dolomite.

The importance of the Catoche as a reservoir unit, then, has direct connections to its position stratigraphically in the subtidal part of the upper cycle, the mudstones and wackestones of which were directly susceptible to diagenetic dolomitization.

Dolomitization

(Notes from Haywick's (1985) thesis: Dolomite within the St. George Gp, Western Newfoundland)

As mentioned above, several attempts had been made to study and characterize the dolomites within the St. George Group (e.g., Collins and Smith, 1975). Haywick (1985) did a Master's thesis on the St. George dolomites which incorporates the up to date revision of the stratigraphy put forward by Knight and James. Haywick's work is thorough and clearly written, and forms the stratigraphic basis for porosity estimation in this study: Haywick's classification of dolomite types was found to be particularly useful by the present author. The pertinent information (i.e., most of the thesis!) is here summarized in point form, with emphasis placed on dolomites and dolostones of the Catoche Formation. The lower formations of the St. George, however, do contain significant quantities of dolomite, particularly the subtidal section of the Watt's Bight, and are included here.

1.1: Purpose: to classify and characterize different varieties of dolomite and dolostone in the St. George

- ten stratigraphic sections were measured in field
- particular emphasis was placed upon the description of dolomite and dolostone
- approximately 450 samples collected/ 375 polished thin sections made, stained with alizarin red-S to differentiate calcite and dolomite, and potassium ferricyanide to qualitatively estimate iron content
- 145 Thin sections repolished and examined by cathodoluminescence, supplemented with electron microprobe data
- selective dolomite and dolostone samples were processed for XRD analysis to ID non-soluble fraction and characterize host carbonate
- C-0 stable isotope analysis performed on 50 limestone, dolomite and dolostone samples/ also Atomic Absorption for Sr^{2+}.

CHAPTER II: Stratigraphic and Sedimentological Framework (Figures 1-4)

2.1 Previous Work: Most recent reassessment of stratigraphic nomenclataure is that proposed by Knight and James - assigned Group status to the St. George and recognized four formations
- little dolomite work done previously
- Daniel's Hbr - sphalerite (Cumming, 1968; Collins and Smith, 1975; Lane, 1984, Kluyver, 1975)
- white "sparry" dolomites have been documented in Lower Ordovician strata from the Table Point area to Cape Norman (Nelson, 1955; Woodward, 1957; Tuke, 1968; Kluyver, 1975; Levesque, 1977; Knight, 1977a, b; 1978; 1980; 1983; Snow and Knight, 1979; Pratt, 1979; Knight and Saltman, 1980; Haywick and James, 1984)

2.2 Measured Sections (used by Langdon in porosity/map calculations)

2.3: Watt's Bight Fm. - type section is at Watts Bight, is approximately 80 m thick, dk gy to black, fine-coarse crystalline, burrow mottled, vuggy, often cherty, stromatolitic and thrombolitic dolostones.
- preservation often spectacular, due to colouration by dolln
- outcrops: St. John Is: partly dolomitized stromatolitic mdstns eastern GNP: bioturb lime mdstns and wckstns eastern P au P area: dolostone is the dominant lith. partially dolld stromatolites and thrombolites abound, form mound complexes
- "remnant" limestone that has apparently escaped regional dolomitization, common in P au P area
- Bioturbation is ubiquitous, giving mottled appearance to dolstones and limestones
- Contact with overlying Boat Harbour Fm along western coast of GNP is marked by limestone, dolostone and chert clast breccias disconformity?

2.4: Boat Harbour Fm - type section located at Boat Harbour near Cape Norman, 120 m thick, predominately composed of bioturbated mudstones and wackestones, locally stromatolitic, grainy, commonly interbedded with finely crystalline dololaminites
- outcrops: lithologies are similar to east in Canada Bay area, and to south in P au P area
- the limestones and dolomites in all areas are characterized by a wide spectrum of shallow water sewdimentary structures and components
-stylolites and pressure solution seams common in Boat HArbour limestones; ichnafossils also very abundant, often preferentially dolomitized. Combination of stylolites/ichnofossils gives rise to characteristic dolomitic mottling of the St. George Gp.
- pebble bed towards top of formation: correlative from western side of GNP south to P au P: disconformity; equivalent erosional surface exposed NW of Canada Bay
- disconformity well exposed on P au P, overlies 14 m of chert- rich, mottled dolostone; punctuated by numerous cavities filled with finely crystalline dolostone which Pratt (1979) interprets as karst solution pipes
- Stouge (1980, 1984) found a hiatus across the pebble bed in Cape Norman area

2.5 Catoche Fm - bioturbated fossiliferous limestones, locally extensively dolomitized. Most complete section crops out at Port au Choix on the GNP where 100m of limestone pass upward into 50 m of medium to coarsely crystalline dolostone (Knight, 1980). This dolostone (prominent) is found everywhere north of Table Point
- in more southerly regions (eastern P au P/Smelt Canyon) the upper interval lacks a coarsely crystalline component
- p.29: description of limestone
- p. 32: description of sponge/stromatolite/thrombolite mounds
- p. 32: top of Catoche in Aguathuna quarry...
- p.32: a prominent dolostone horizon found north of Table Pt; contains alternating sequences of dull grey, medium crystalline dolostone, andcreamcoloured, coarselycrystallinedolostone. Both varieties are mottled by a finer, darker dolomite and can be very porous and bituminous (Knight and Saltman, 1980). White sparry dolomnite crystals up to 15mm in size are common and localized in vugs and as fracture fill cements (associated with sphalerite mineralization in Daniels Harbour area)

2.6 Aguathuna Fm. - disconformity with Catoche on St. John Island (Port au Choix)
- at Table Pt, appears conformable; 60m thick, finely crystalline dololaminites
- much less dolomitic in Hare Bay/P au P areas, sparse shelly fauna, but many oncolites and stromatolites
- Aguathuna thins away from type section at Table Point
35m at Hare Bay
50m at Aguathuna
10m at Port au Choix
- entombed sulphate crystallites suggest that evaporates may have existed, chert breccias may have formed through dissolution and subsequent collapse. Other workers believe breccias were related to subaerial exposure.
- p.35 - contact with Table Head an erosional channel (9m at Aguathuna), silcrete horizon developed during exposure. Elsewhere on P au P contact appears conformable or poorly exposed - pressure solution seams visible at Aguathuna

2.7: Facies interpretation (omitted here)

CHAPTER III. Field Characteristics of Dolomite and Dolostone (Figure 5a (pdf - 393kb)) (Figure 5b (pdf - 413kb)) (Figure 5c pdf - 478kb))

3.1 Introduction: four varieties of dolostone (>50% dolomite) and two varieties of dolomitic limestone (<50% dolomite) in the St George. Four dolostones referred to as (1) dololaminites (2) pervasive A dolostone (3) pervasive B dolostone (4) cavity-filling dolostone
- two dolomitic limestones contain dolomite as either matrix or mottle dolomite
- also saddle (coarse, sparry) dolomite fills void space and fractures in pre-existing rocks: Genetically related to pervasive B dolostone.

Distinguishing Parameters
1) crystal size; 2) proportions of dol within a limestone unit; 3) faunal content, or lack thereof; 4) degree and nature of mottling; 5) sedimentary structures; 6) colour; 7) localization
- stratigraphic/geographic distributions of seven varieties are summarized in tables (here reproduced as Figure 5a) and on ten measured sections

3.2 Dololaminites
Definition and Description: characterized by fine, often cryptalgal laminations, with dark organic material; cross- laminated, tepee structures, dessication cracks
- weathering: buff to black, microcrystalline to very finely crystalline dolomite. Fenestral, chert, vugs (spar filled), in short textural variability
- bed thickness: few cm -> 3m; beds coalesce into thicker units
- stylolites: commonly bound beds
- frequently fractured, rubbly
- stained red on P au P , Liesegang banding
Stratigraphic and geographic distribution: confined to Boat Harbour, Aguathuna and basal Watts Bight Fms

3.3 Matrix Dolomite - selectively replaces matrix/intergranular areas in packstones and grainstones. Allochems usually unaltered. Dolomite rhombs are medium crystalline white or medium gray weathering; 5-40% replacement of limestone is common
- intervals are of very limited vertical extent; usually separated from other types by stylolites
- in coarse limestones, matrix dolomite-rich intervals may be up to I m in thickness, buff-rust, contain abundant intercrystalline porosity, pore-filling calcite cement and black (organic rich) material. Bituminous odour on fresh surfaces - intercrystalline gaseous hydrocarbons
- Stratigraphic/geographic distribution: (only 1-2% of all dolomites) - best developed in packstones of Watt's Bight and Boat Harbour Fms in P au P area (Isthmus Bay and Berry Head).

3.4 Mottle Dolomite
Definition and Description: replaces specific components within limestones; buff/light gray, finely crystalline; many ichnofossils, stylolites, Maclurites (spiral gastropods)
Mottle dolomite: often has a salt and pepper appearance due to combination of light-coloured dolomite crystals, and dark intercrystalline porosity. Lichen preferentially grow within the mottles.
- trace fossils abundant, but not diverse. Various amounts of dolomite associated with these components
- in many limestones, mottle dolomite is localized partially or entirely along pressure solution seams and stylolites - amount of mottle dolomite ranges from trace to 40%
- limestones containing the most mottle dolomite are usually fine- grained wackestones and mudstones

Stratigraphic/Geographic distribution:
- most widespread variety within the St. George GP., present and laterally continuous almost everywhere
- mostly due to a combination of ichnofossils and stylo.lites; only occasional "burrow-only" or "stylolite-only" mottles

3.5 Pervasive Dolostones: distinctive mottled appearance, mottled areas composed of darker, finer dolomite than interareas. Two types:

Pervasive A:
Interareas, because of coarser dolomite crystal size, are more porous than the mottled intervals, and as a result, may contain minor amounts of pore-filling calcite cement. Slight to strong bituminous odour when broken.
- mottles account for 50-80% volume of these dolostones, and are usually nondescript
- pervasive-A dolostones commonly grade vertically or laterally into dolomite mottled limestones stromatolite/thrombolite horizons are recognizable; dolamitization of mounds and biohermal buildups is variable; often the mound itself is unaltered, while intervening sediment is dolomitized
- bed thickness usually 30 cm - 2m; but sequences up to 15m present
- generally stratabound dolomite

Pervasive B:
interareas composed of white to pink, coarsely crystalline dolomite (1-5mm) -> gives rock a light pink-grey colour.
- proportion of dark mottles seldom exceeds 40% of host, can often be clearly idenfitfied as ichnofossil traces. Gastropods conspicuous on bedding planes
- stromatolites and thrombolites in moundy intervals are replaced by the coarser, lighter colour dolomite rather than by the finer, darker dolomite.
- interareas between mottles exhibit abundant intercrystalline porosity. Pore space is often filled by calcite, chert, fluorite or quartz, but also by a black bituminous material, which on analysis yielded 0.26 mg/g of insoluble organic extract. This hydrocarbon is likely strongly biodegraded, and now contains no normal paraffins (R. Quick, pers. comm., 1984).

Extent and Distribution of the Pervasive-B Dolostone
- exceedingly variable, some beds laterally continuous over hundreds of metres of section; other beds are discontinuous after a few metres. This results in "remnant" limestone intervals within otherwise pervasively dolomitized strata. Contacts between the two rock types are sharp, but no clues to this sharp break are given in the original limesstone lithologies, which tend to be homogenous mudstones or wackestones.
- also tends to be localized in distinct equidimensional "pods" or flat-lying "pans" within limestones; again these show sharp contacts and are localized along fractures and joints, or are stratabound. Some occurrences may represent preferentially dolomitized stromatolite or thrombolite mounds.

Stratigraphic and Geographic Distribution of Pervasive Dolostones

Pervasive-A dolostone is very widespread, found in all formations of the St. George, and in every major outcrop. The upper portion of the Catoche Formation contains this lithology in all sections studied; minor beds are present in the lower part of the formation. The other three formations of the St. George contain pervasive-A dolostone in varying amounts; in particular the Watt's Bight Formation and the Aguathuna Formation on the Port au Port have significant quantities of this type. Appears to be generally less abundant in the northern areas.

Pervasive-B dolostones, however, are restricted entirely to outcrops on the GNP; again they are here found within all four formations of the St. George Group
- very common in the Watt's Bight, less abundant in the Boat Harbour Formation, and rare in the Aguathuna.
- Catoche Fm. : thick sequences of pervasive-B dolostone coalesce and become interbedded with the pervasive-A dolostones; these are the "diagenetic dolostones" of Knight (1977b; 1980) and Pratt (1979) and are regionally correlative everywhere on the Northern Peninsula.

3.6 Saddle Dolomite
- found in fractures, veins and vugs within other rocks.
- crystals, white to. pink, coarse (1-15mm) , usually curved and distorted.
- contains abundant intercrystalline porosity, often filled by bituminous material, calcite or chert. Centres of vugs and fractures may contain open voids up to several cm in diameter.
- this lithology is well developed in the vicinity of the Daniel's Harbour zinc mine, where it develops a fabric referred to as "pseudobrecciall (Collins and Smith, 1975; Lane, 1984; 1990). These are rocks composed of horizontally oriented, dispersed and angular patches of mottle dolomite "floating" in a saddle dolomite cement.
Clasts in the pseudobreccia show no displacement or rotation, as opposed to those of true breccias.
- saddle dolomite is pore-filling: it appears to grow from the margins of open spaces, mainly fractures and vugs, inward to the centre of these spaces.
- saddle dolomite can also replace part of the country rock adjacent to fractures, and finely crystalline dolomite that is the matrix to some breccias near the mine

Stratigraphic and Geographic distribution:

- located principally within pervasive-B dolostone rich intervals on the GNP. Particularly abundant in the

upper third of the Catoche Formation, especially at Table Point and Daniel's Harbour.
- common in the Watt's Bight and Boat Harbour Formations, not common within the Aguathuna.

3.7 Cavity-Filling Dolostone
- occurs in small (<30 cm) irregularly shaped cavities within pre- existing pervasive-A and B dolostone.
- buff to green, very finely crystalline (<50 micrometres) , usually geopetal
- cavities cut cryptalgal laminations and mottle dolostone, but do not cut veinlets of saddle dolomite in pervasive-B dolostones.

Stratigraphic and Geographic Distribution

- least abundant volumetrically of the St. George dolomites, best examples are associated with the stromatolitic-thrombolitic mound- rich prevasive-B dolostones of the Watt's Bight formation at Cape Norman and on New Ferolle peninsula (north of Port au Choix)

CHAPTER FOUR:
Petrography, Cathodoluminescence, and Paragenesis

4.1 Introduction

4.2 Cathodoluminescence of Carbonates
- several paragraphs on theory and methods

4.3 Limestones
- in order to understand the diagenetic events responsible for dolomite, paragenetic history of the limestones must be understood.
- diagenetic events affecting St. George limestones can be divided into three stages: 1) syngenetic (or synsedimentary) 2) early diagenetic (eogenetic, Choquette and Pray, 1970) 3) intermediate to late diagenetic (Mattes and Mountjoy, 1980; mesogegnetic of Choquette and Pray, 1970)

Cements:
- three generations of calcite cement are recognized (Smit, 1971; Pratt, 1979). Haywick, fig,. 4.2)
(1) Radial bladed calcite cement (syngenetic) : predates pore filling by lime mud, probably precipitated out of well-oxygenated sea water during and/or immediately after deposition (Grover and Read, 1983).
(2) Syntaxial calcite spar (syngenetic to early diagenetic) occurs as overgrowths around echinoid fragmetns and ooids; commonly abut into radial bladed calcite cement, implying either cogenetic, or later growth than the radial bladed calcite.
(3) equant calcite (intermediate to late diagenetic) . Most abundant cement in St. George grainstones and is a common second stage cement to grainstones cemented previously by radial or syntaxial cements. Crystals range from .30 - 200 micrometres. Pratt (1979) interprets it as a "mesogenetic" burial cement precipitated from phreatic pore waters under predominantly reducing conditions, with accompanying minor fluctuations in redox potential or in pH (Hem, 1972: Grover and Read, 1983).

Aragonitic Components: - aragonite body fossils affected by an episode of dissolution near the seafloor, or very soon after burial - thus, their diagenesis was restricted to syngenetic or early diagenetic dissolution (fig 4,2).

Silicification - early diagenetic event, preserves the original fabrics of grains and cements.

MUDSTONE LITHIFICATION AND MICROSPAR GENESIS

- lithification of lime mud in mudstones and wackestones is a relatively early diagenetic event (based on only slight compaction of trace fossils)
- micrite in these fine grained limestones is commonly altered to microspar (finely crystalline, 5-20 um). Microspar also appears to have both formed directly from unlithified mud (Steinem, 1978, 1982; Lasemi and Sandberg, 1984) as an early diagenetic product, and also during late-diagenetic periods of tectonic

fracturing.

PRESSURE SOLUTION AND TECTONIC FRACTURING

- pressure solution results in a variety of stylolite forms; considered a late diagenetic event
- tectonic fracturing and fill by a variety of calcites. Occurred several times during diagenesis, but is commonly the last diagenetic event (fig 4.2). Some of this infill is as young as Carboniferous.

4.11 Dolomitization synopsis
Four generations of dolomite are distinguished, with seven field varieties:
1) Dololaminites are syngenetic, deposited in tidal flat environments. Generally finely crystalline, uniformly luminescent anhedral dolomite.
2) Matrix dolomite in fine grained limestones, and Mottle dolomite: formed by early to late-diagenetic (i.e., long-lived) events. Pervasive-A dolostones represent earlier phases. Diverse and varied petrographic and luminescence character appears to reflect local water chemistry.
3) Matrix dolomite in coarse grained limestones, Saddle dolomite, Pervasive-B intermottle dolomite: late diagenetic, characterized by coarse, uniformly luminescent, strained dolomite crystals. Pervasive-B dolostones overprint pre-existing dolomite-mottled limestones (or in the Watt's Bight, pre-existing pervasive-A dolostone). Related to tectonics.
4) Cavity-filling dolostone: fills cavities created by subaerial exposure.

CHAPTER VII: MECHANISMS OF DOLOMITIZATION AND CONCLUSIONS

7.2 Mechanisms of Dolomitization
(Figure 6a (pdf - 406kb), Figure 6b (pdf - 518kb), Figure 6c (pdf - 495kb), Figure 6d (pdf - 458kb), Figure 6e (pdf - 701kb), Figure 6f (pdf - 438kb), Figure 6g (pdf - 220kb), Figure 6h (pdf - 251kb), includes a series of figures from Haywick (1985) which illustrate mechanisms for the generation of the various dolomite types).
- (dololaminite omitted here)
- Early Diagenetic Dolomitization: Mottle Dolomite, Matrix Dolomite (in fine-grained limestones), Pervasive-A Dolostone

1) Nucleation
- ichnofossils are more permeable then the enclosing limestone (Kendall, 1977; Morrow, 1978a); trace fossils act as conduits for dolomitizing fluids. Kendall's work demonstrates that some mottle dolomite formed early in the diagenetic process by replacement of the unlithified components, such as ichnafossils and gastropod molds. Such unlithified mud intervals or beds may have been the predecessors of pervasive-A dolostones.
- organic linings of trace fossils (e.g., Paleophycus) may have promoted dolomitization (1) by removing sulphate during biogenic decay (reduction; Lippman, 1973; Kastner, 1984), or (2) by concentrating Mg2+ through organic completing (Gebelein and Hoffman, 1973).
- Regarding the first process, Haywick thinks that some of the dolomite could have formed by biogenic decay and reduction of sulphate.
- Regarding the second process, sulphate ions may have been removed by organic completing, providing a mechanism of dolomite nucleation in the absence of nucleating conditions. This would occur following bioturbation and lithification of the lime mud surrounding the ichnofossil, where sulphate completing could have removed S04 2- from the area enclosed by the organic lining. Dolomite nucleation could occur as sub-micron sized crystallites, forming substrates for early and late diagenetic growth. Dolomite growth then proceeded wherever and whenever fluids and conditions favourable for dolomitization occurred.

2) Nature of Dolomitizing Fluids
- concomitant dissolution and precipitation enabled dolomite growth after nucleation.
- generation of pervasive-A dolostones in particular could be explained by mixed water dolomitization (mixing of seawater with meteoric water, e.g., Folk and Land, 1975; Kastner, 1984).
- could also explain localization of pervasive-A dolostones beneath suspected or documented subaerial exposure horizons

- some of the isotopic variation observed in prevasive-A dolostones could be a result of mixing seawater with freshwater in different proportions
- both dololaminites and pervasive-A dolostones developed when unlithified sediments were occasionally subaerially exposed; pervasive-A dolostones formed in areas where meteoric water (rather than seawater) contributed significantly to the pore fluids. Development of exposure horizons at the top of sequences of pervasive-A dolostone (e.g., St.George Unconformity on the Port au Port peninsula) imply longer periods of exposure.
- Pratt's (1982) argument against pressure solution as a cause of widespread stratigraphic burial dolomite (pervasive-A dolostones) is supported by Haywick, although Haywick believes some mottle dolomite in the St. George has grown wholly along stylolites, and may have accompanied pressure solution. Solution of limestone could have produced calcium which may have reacted with Mg-bearing fluids passing along stylolites.

- Late-Diagenetic Dolomite: Pervasive B Dolostone, Saddle Dolomite and Matrix Dolomite (in coarse-grained limestones)

- pervasive-B dolostone and saddle dolomite on the GNP are the result of a late diagenetic event involving hydrothermal fluids; matrix dolomite on the Port au Port is more limited in extent but probably has a similar origin.
- hydrothermal fluids are thought to be derived through the de- watering of basinal sediments during burial metamorphism (Barnes, 1983). Isotope analysis suggests that precipitation of St. George saddle dolomites and pervasive-B dolostones range from 37 to 64 degrees C.
- saddle dolomite associated with sphalerite mineralization near Daniel's Harbour; transport mechanisms for zinc and sulphide were of local extent compared to the widespread distribution of the pervasive-B dolostones and saddle dolomite.

7.3 Dolomitization and Proposed Sedimentation Modes

7.4 Further Study (these suggestions may be useful in proposing any further studies)

Tectonics, The St. George Unconformity, Mineralization, And Deep Basinal Fluid Flow: Their Relationship To Dolomitization

Lane (1990) in a Ph. D. thesis at Memorial entitled "Dolomitization, brecciation and zinc mineralization and their paragenetic, stratigraphic and structural relationships, Upper St. George Group - Ordovician - Daniel's Harbour, western Newfoundland", has now just recently added a whole new body of knowledge to the St. George in western Newfoundland, and the GNP in, particular. Lane's work is interesting: not only does he describe lithologies and paragenesis of ores and their dolomite host rocks, but also puts forth ideas for the cyclic stratigraphy and unconformity development that supplement the earlier work of Knight and James (1987), and others. In particular, his consideration of both eustatic and tectonic models for the cyclic stratigraphy of the Aguathuna Fm. contribute to a recent paper relating the St. George Unconformity to plate convergence, by Knight, James and Lane (1991). These papers are the main source of my following discussion on the relationship between tectonic (i.e., burial/uplift) events and the Catoche dolomites. (N.B., Lane classifies the dolomites somewhat differently than Haywick, although their essential characteristics are the same. A comparison of the two is shown in Figure 7).

The Unconformity and Effects on the Catoche During Early Burial

The St. George Unconformity is a karst unconformity to disconformity to paraconformity, and forms the sequence boundary separating the Lower and Middle Ordovician systems in western Newfoundland. It is associated with a flexure in the lithosphere and forebulge on the continental shelf created in the early stages of the Taconian Orogeny. This uplift begins at the end of Lower Aguathuna time, and initiated erosion of the St. George platformal carbonates, which would have been mainly Catoche; locally up to 50 m of strata were removed from block-faulted highs. The faults also controlled groundwater f low and dissolution of the carbonates, which resulted in subsidence dolines at the unconformity surface and the accumulation of thick pre-unconformity carbonate sediments (generally dololaminites) of the middle

Aguathuna Fm.

The karst terrane created by the unconformity plays a further role in the development of dolomites within the underlying Catoche. Subsurface karst penetrating to some 120 m below the unconformity developed near surface-porosity and deeper, structurally controlled caverns which accumulated muds, chert sands, and rock matrix breccias. Stoping above the caves led to further subsidence dolines and relief at the surface. Pebble lags at the surface are eventually onlapped by the transgressive (peritidal) deposits of the upper Aguathuna member. Early finely crystalline dolomite selectively replaced peritidal mudstone beds of the upper St. George during this time.

Knight, James and Lane (1990) conclude that the unconformity is wholly tectonic in origin, and is not caused by eustatic sea level lowering.- "the whole complex of sediments, faults, and erosion surfaces is best explained by slowing to cessation of subsidence and gradual passage of a forebulge across the paleocontinental margin".

The Catoche During Deep Burial: Hydrothermal Influence of the Acadian Orogeny
(Figure 8 (pdf - 132kb) and Figure 9 (pdf - 191kb))
As the platform continued subsiding and shallow marine carbonates of the middle Table Head Group accumulated, the Catoche Formation continued to experience dissolution-related brecciation, and fine dolostone infill in the breccia matrix. Subsequently, the St. George was buried to a depth of 700-1500 m by flysch (Goose Tickle, 700+ m) and allochthons (500 m) , and the Catoche limestones were extensively and progressively recrystallized and dolomitized. Figure 8 summarizes these and later stages in a burial/diagenesis curve. This would correspond to the diagenetic stages of matrix, mottle and pervasive-A dolomites of Haywick (Figure 8, burial curve).

Based upon thermal maturation data (CAI 2 - 2.5, Nowlan and Barnes, 1987) the platform is estimated to have been buried to depths between 2 and 3 kilometres from the late Ordovician to the late Silurian. Subsequently, in the early Acadian orogeny, the platform was deformed along reactivated northeast-trending faults in response to regional compression. Linear, strata-bound fracture systems served as conduits for the migration of hydrothermal brines and resulted in the generation of coarse dolostone-sphalerite bodies. The effects of these fluids on the Catoche can be understood in three stages: (1) the f irst fluids dolomitized upper Catoche limestones and overprinted earlier matrix, mottle and pervasive-A dolostones along fractures. (2) Subsequent higher temperature ore fluids partially dissolved carbonates. (3) Multiple layers of sphalerite precipitated through the area now exposed at the Daniel's Harbour mine; fracturing and dissolution continued while fluid temperatures decreased. Dilation of earlier fractures led to widespread post-ore dolomitization which overprinted earlier medium-coarse crystalline dolostones (matrix, mottle, pervasive-A and early pervasive-B) and further replaced limestones. The first phase of saddle dolomite (saddle A of Lane) then filled veins and solution pores, again partially replacing earlier dolostones. The later stage saddle (B) dolomite along with calcite and sulphates precipitated in pore space as late fluids progressively cooled (to 50 degrees C).

Catoche Saddle Dolomites: Late Acadian Reaional UDlift and Carboniferous Overprint
(Figures 8 and 9)
This late stage of saddle B dolomitization continued as the platform fragmented and was displaced along faults during the late stages of the Acadian Orogeny. Near the faults, discordant saddle B dolostones replaced limestones, and some dolostones developed above thrust faults during syntectonic fluid migration.
Finally, during the Carboniferous, faulting and fracturing associated with strike-slip tectonics resulted in the circulation of meteoric waters and the creation of ubiquitous vuggy porosity. This was partially cemented by late saddle dolomites and calcites.

Lane's Thermal Convection Model: Implications for Hydrocarbons (Figure 9)
Although this burial curve and cross sectional model were developed by Lane (1990) for dolomite/ore paragenesis, it can be used to make preliminary predictions about hydrocarbon generation and migration. A common explanation for the movement of basinal waters is recharge in terrestrial (i.e., mountainous) regions and gravity-driven flow caused by the hydraulic head. Lane, however, believes that in western

Newfoundland thermal convection above an elevated geothermal gradient could have driven fluid movement: fluids would have moved up steep basement-related fracture systems. Such an origin would better explain the source of the dolomitizing hydrothermal fluids. On Figure 9 the Port au Port peninsula and the Mobil acreage would lie to the west of the area of Taconian allochthon overthrusting and Acadian basement fracturing. This area would have lain updip of "depressed" platformal rocks involved in the epithermal/hydrothermal dolomitization and mineralization. If the fossiliferous platformal rocks can be considered to have some potential for self-sourcing, hydrocarbon generation could have been initiated by the elevated geothermal gradient in the deep basin. These hydrocarbons could have migrated upward and westward with the dolomitizing fluids and have been emplaced in reservoirs of diagenetic dolomite (porous diagenetic pervasive-A dolomites occur on the Port au Port and Smelt Canyon).

Given the somewhat poorly understood effect of Carboniferous strike-slip tectonics on the position of Lower Paleozoic strata, there is some question as to the original relative positions of the Northern Peninsula and Port au Port field areas. However, it does seem that the southern area may have lain to the west, since the pervasive dolomites on the Port au Port are diagenetic, and do not rely on deep burial for their porosity. These rocks would have developed some early porosity prior to fluid migration and structuring associated with the Acadian Orogeny; it seems that the potential for charging extensive stratigraphic traps is real. Alternatively, charging of syn- and post-Acadian structural traps (such as those associated with the "triangle zone") could be considered.

Point Counting, Photomicroscopy And Porosity Determination

A total of 64 thin sections were examined for the purpose of lithology determination and porosity measurement by point counting. Thin sections were stained with Alizarin Red-S to differentiate calcite from dolomite. Most of these thin sections were photographed, at low power. The dolomite classification scheme of Haywick outlined earlier in this report was used to group samples so that associations of lithology and porosity could be made. These results are tabulated in Table 1 and Table 2. Data from the average porosity sheet were then combined from stratigraphic column data to calculate various map data points.
A representative suite of photomicrographs and concomitant field photos is presented in Plates 1-14 (pdf - 428kb).

Porosity Maps Of The Catoche Dolomites

Five types of maps were generated to display the distribution and nature of Catoche porosity in dolomites. Porosities were calculated, where possible, by thin section examination and point counting. Eight measured sections of Haywick (1984) which included Catoche outcrop were used as the main stratigraphic data points (Figure 10 (pdf - 302kb)): Cape Norman, Back Arm, Port au Choix, Table Point, Smelt Canyon, Isthmus Bay, and Aguathuna. These sections were combined with the author's field work in the following way: stratigraphic sections from the Port au Choix and Back Arm localities were combined with porosities measured from the Port au Choix (PC) samples, Table Point section with TP and DH (Daniel's Harbour) samples, Smelt Canyon with Table Mountain (TM) and Table Mountain North (TMN) samples, Isthmus Bay section with IB samples, and Aguathuna with A samples. For the Cape St. George (CSG) samples stratigraphic thicknesses for the Catoche were taken from a cross section contained in Knight and Cawood's west coast field guide (CERR short course, 1991) ; thicknesses for the Ship Cove (SC) samples were taken by averaging CSG and IB thicknesses.

(1) Field stop locations, dolomite types, and porosity occurrence maps: one each for the Port au Port, Table Point and Port au Choix field areas. These maps include stratigraphic boundaries and faults. Another map for diamond drill core data from the Daniel's Harbour area is included (sample locality map 4 (pdf - 127kb)).

(2) Porosity thickness map (thickness of porous Catoche dolomite): western Newfoundland, includes outline of St. George outcrop areas).

(3) Quantitative porosity map (thickness * porosity, or phi-h)

(4) Qualitative porosity map - this map was constructed by plotting the summed values for the most porous dolomites - the pervasive-A and pervasive-B dolomites.

(5) **Dolomite/total Catoche ratio map** (dolomite/[dolomite + limestone]).

Discussion and Results of the Porosity Study
Maps and summary tables are found on the following pages. As a general comment, it seems that the porosities measured from thin sections represent a minimum porosity for the given sample, because this method estimates only microscopic (intercrystalline and microvuggy) porosity accurately. Vuggy and cavernous porosity, such as is abundant in the pseudobreccias of the Daniel's Harbour area, is estimable only in cores or hand specimens. With this in mind, 5% has been added to the average porosities of the generally coarse pervasive-B dolostones, as seen in Table 2. This appears to fit well with the 15-25% porosities estimated over many zones in the Daniel's Harbour area drillcores.

Dolomitic rocks of the Catoche Formation have been found in this study to contain abundant porosity. The non-pervasive (matrix and mottle) dolomites have highly variable but generally low porosity (< 7%, Table 2). The pervasive-A and -B dolostones, however, show a range to much higher porosities, although have low porosities as well. Pevasive-B dolostones show the highest values, and as discussed above, their values may be reasonably expected to be higher by at least 5% due to macroscopic vuggy porosity. By the same token, the pervasive-A dolostone porosity may also be enhanced, albeit to a lesser degree, by vugs; therefore the average value of 4.3% for pervasive-A dolostones is considered conservative.

Sample Location Map 1 (pdf - 183kb)   Sample Locality Map 2 (pdf - 162kb)

Sample Location Map 3 (pdf - 128kb)   Sample Locality Map 4 (pdf - 127kb)

Examination Of Daniel's HBR. Cores At The Pasadena Core Facility

On the advice of Dr. T. Lane, the following five cores were examined for porosity (Sample Locality Map 4):

DDH-2	Goose Tickle - Table Head - Catoche	TD 1658'
DH-895	Catoche? (called "lower" St. George in log)	TD 298m
DH-896	Catoche (" " ")	TD 194m
DH-935	Table Head - St. George (Agua/Catoche)	TD 450m
DH-939	Table Head - St. George a/a	TD 336m

The original geologists' logs are here reproduced with my annotations and calculations of porosity for the lithological zones described in the logs. The major dolomite type in these holes is pervasive-B, with less pervasive-A and minor mottle dolomite.

Map 1 (pdf - 173kb)   Map 2 (pdf - 162kb)   Map 3 (pdf - 153kb)   Map 4 (pdf - 162kb)

Bibliography And References

The following bibliography is a listing of the literature and resource materials that were directly used or obtained by the author in compiling this report. These are available at Memorial University either in my files or in the university libraries. Some materials such as these cannot be removed from the libraries. This is followed by a listing of references - papers referred to in the literature used in writing this report.

BIBLIOGRAPHY

Badiozamani, K. 1973, The dorag dolomitization model application to the Middle Ordovician of Wisconsin. Journal Sed. Petrology, v. 43, pp. 965-984

Boyce, W. D., 1983b: Early Ordovician trilobite faunas of the Boat Harbour and Catoche Formations (St. George Group) in the Boat Harbour - Cape Norman area, Great Northern Peninsula, western Newfoundland. Unpub. M. SC. thesis, Memorial University of Nfld.

Choquette, P. W., and Pray, L. C., 1970: Geologic nomenclature and classification of porosity in sedimentary carbonates. AAPG Bull., v. 54, p. 207-250.

Collins, J. A., and Smith, L., 1975: Zinc deposits related to diagenesis and intrakarstic sedimentation in the Lower Ordovician St. George Formation, Western Newfoundland. Bull. Canadian Soc. Petroleum Geology, v. 23, no. 3, pp. 393-427

Dreybrodt, W., 1988: Processes in Karst Systems. Springer-Verlag. Berlin, 288 p.

Dunham, J. B., and Olsen E. R., 1978: Diagenetic dolomite formation related to Palaeozoic palaeogeography of the Cordilleran miogeocline in Nevada. Geology, v. 6, pp. 556-559

Haywick, D. W., 1985: Dolomite within the St. George Group (Lower Ordovician), Western Newfoundland. M. SC. Thesis, Memorial University, 281 p.

Haywick, D,W., and James N. P., 1984: Dolomites and dolomitization of the St. George Group (Lower Ordovician) of western Newfoundland. In current research, part A, Geological Survey of Canada, Paper 84-1A, pp. 531-536

James, N. P. and Choquette, P. W., eds., 1988: Paleokarst. Springer-Verlag, 416 p.

James, N. P and Stevens, R. K., 1986, Stratigraphy and correlation of the Cambro-Ordovician Cow Head Group, western Newfoundland. Geological Survey of Canada Bulletin 366, 143p

Knight, I. , 1977: The Cambrian-Ordovician platformal rocks of the Northern Peninsula, Newfoundland. Newfoundland Dept of Mines and Energy, Mineral Development Division, Report 77-6

------- 1978: Platformal sediments an the Great Northern Peninsula: stratigraphic studies and geological mapping of the north St. Barbe district. In Report of Activities for 1977. Ed. R V. Gibbons, Newfoundland Dept of Mines and Energy, Mineral Development Division, Report 78-1, pp. 140-150

------- 1980a: Geological mapping of parts of the Eddies Cove, Salmon River and adjacent map areas. in Current Research, ed. C. F. O'Driscoll and R. V. Gibbons, Newfoundland Departmment of Mines and Energy, Mineral Development Division, Report 80-1, pp. 1-9

------ 1980b: Cambro-Ordovician carbonate stratigraphy of western Newfoundland: sedimentation, diagenesis and lead-zinc mineralization. Newfoundland Department of Mines and Energy, Mineral Development Division, Open File Nfld. 1154

------ 1983: Geology of Cambro-ordovician rocks in parts of the Castor River, St. John Island and Port Saunders map sheets in Current Research, ed. M. J. Murray, P. D. Saunders, W. D. Boyce and R. V. Gibbons. Newfoundland Departnment of Mines and Energy, Mineral Development Division, Report 83-1, pp. 1-10

Knight, I. and James, N. P., 1987: Stratigraphy of the Lower Ordovician St. George Group, western Newfoundland: the interaction between eustasy and tectonics. Canadian Journal of Earth Sciences, v. 24,

p. 1927-1951

Knight, I., James, N. P, and Lane, T. E., 1991: The Ordovician St. George Unconformity, Northern Appalachians: The relationship of Plate Convergence at the St. Lawrence Promontory to the Sauk/Tippecanoe Sequence Boundary. Geol. Soc. America Bulletin, v. 103, p. 1200-1225.

Kunkle, D., 1986: Fracture system and hydraulic and acoustic properties of bedrock at Parsons Pond, western Newfoundland. unpub. B.Sc. thesis, Memorial University of Newfoundland.

Lane, T. E., 1984: Preliminary classification of carbonate breccias, Newfoundland zinc mines, Daniel's Harbour, Newfoundland. in Current Research, Part A, Geol. Surv. Canada, Paper 84-1A, pp. 505-512

Lane, T. E., 1990: Dolomitization, brecciation and zinc mineralization and their paragenetic, stratigraphic and structural relationships, Upper St. George Group - Ordovician - Daniel's Harbour, western Newfoundland. Ph. D. thesis, Memorial University of Newfoundland, 565 p.

Levesque, R. J., 1977: Stratigraphy and Sedimentology of Middle Cambrian to lower Ordovician shallow water carbonate rocks, western Newfoundland. M. Sc. thesis, Memorial University of Newfoundland.

Logan, B. W., 1988: The MacLeod Evaporite Basin of western Australia. A.A.P.G. Memoir 44, 140 p.

Machel, H. G., 1991: Sour Gas Generation and Dolomitization. Illustrated Lecture Notes for short course to Mobil Oil Canada, June 20, 1991

Machel, H. G., 1987: Saddle dolomite as a by-product of chemical compaction and thermo-chemical sulfate reduciton : Geology, v. 15,pp. 936-940

Machel, H. G., and Mountjoy, E.W., 1987: General constraints on extensive pervasive dolomitization - and their application to the Devonian carbonates of western Canada. Bull. Canadian Petroleum Geology, v. 35, no. 2, pp. 143-158

McIlreath, I. A., and Morrow, D. W./ eds., 1990: Diagenesis. Geoscience Canada Reprint Series 4.

Nichols, K.M., 1980: Depositional and diagenetic history of dolomitized grainstones at the top of the Madison Group, Disturbed Belt, Montana. in: T. D. Fouch and E. R. Magathan, eds. , Rocky Mountain Paleogeography Symposium 1, Paleozoic Paleogeography of the West-Central United States: Rocky Mountian section, S.E.P.M., p. 163-173

-------- 1984: Stratigraphy of the upper part of the Madison Group, Sawtooth Range, northwestern Montana. in: J. D.McBane and P. B. Garrison, eds. , Northwest Montana and adjacent Canada. Montana Geol. Soc. 1984 Field Conference and Symposium, p. 127-140

Oliver, J., 1986: Fluid expelled tectonically from orogenic belts: their role in hydrocarbon migration and other geologic phenomena. Geology, v. 14, pp. 99-102

Pratt, B. R., 1979: Sedimentology, diagenesis and cryptalgal structures, the St. George Group (Lower Ordovician) , western Newfoundland. M. Sc. thesis, Memorial University of Newfoundland.

Radke, B. M. and Mathis, R. L., 1980: On the formation and occurrence of saddle dolomite. Journal of Sedimentry Petrology, v. 50, pp. 1149-1168

Sando, W. J. , 1988: Madison Limestone Paleokarst, a geologic synthesis. in: James, N. P. , and P. W. Choquette, eds. , Paleokarst. New York, Springer-Verlag, P.256-277

Ward, W. C. amd Halley, R. B., 1985: Dolomitization in a mixing zone of near seawater composition, Late Pleistocene, northeastern Yucatan Peninsula. Journal Sedimentary Petrology, v. 55, no. 3, p. 407-420

Zenger, D. H. and Mazzullo, S. J., 1982: Dolomitization. Benchmark Papers in Geology/65. Hutchinson Ross Pub. Co., Stroudsberg, Pennsylvania, 426 p.

REFERENCES

Adams, J.E. and Rhodes, M.L. , 1960: Dolomitization by seepage refluxion. A.A.P.G. Bull., v. 44, p. 1912-1920

Barnes, H. L., 1983: Ore depositing reactions in Mississippi Valley-type ore deposits. in: G. Kisvarsanyi and S. K. Grant, International Symposium on Mississippi Valley-Type Pb-Zn deposits, Univ. of Missouri, Rolla, pp. 77-85

Besaw, D., 1974: Limestone evaluation, Port au Port Peninsula. In Limestone resources of Newfoundland and Labrador. ed. J. R. DeGrace, Nfld. Dept. Mines and Energy, Report 74-2

Boyce, W. D., 1983a: Early Ordovician trilobite faunas of the Boat Harbour and Catoche Formations (St. George Group) in the Boat Harbour-Cape Norman area, Great Northern Peninsula, western Newfoundland. M. Sc. thesis, Memorial University of Nfld., 272 p.

-----------, 1985: Cambrian-Ordovician biostratigraphic investigations, Great Northern Peninsula, western Newfoundland. in: Current Research, K. Brewer, et. al. , eds. , Nfld. Dept. of Mines and Energy, Mineral Development Division, Report 85-1, 60-69

Collins, J. A., and Smith, L., 1972: Sphalerite as related to the tectonic movements , deposition, diagenesis and karstification of a carbonate platform. 24th International Geological Congress, Secion 6, pp. 208-215

--------, 1973: Lithostratigraphic controls of some Ordovician sphalerite. in: Amstutz, G.C. and Bernard, A. J. (eds.) , Ores in Sediments. Heidelberg, Springer-Verlag, pp. 79-91

Cumming, L. M. , 1968: St. George - Table Head disconformity and zinc mineralization, western Newfoundland. Canadian mining and Metallurgical Bull., 61, 721-725

-------- 1983: Lower Paleozoic autochthonous strata of the Strait of Belle Isle area. in Geology of the Strait of Belle Isle area, northwestern insular Newfoundland, southern Labrador and adjacent Quebec. edited by H. H. Bostock, L. M. Cumming, H. Williams and W. R. Smith. Geol. Surv. Canada, Memoir 400, Map 1495A

Dixon, J., 1976: Pattern carbonate - a diagenetic feature. Bull. Canadian Soc. Petroleum Geologists., v. 24, pp. 450-456

Fisher, W.L., and Rodda, P.V., 1969: Edwards Formation (Lower Cretaceous) Texas: Dolomitization in a carbonate platform system. A.A.P.G. Bull, v. 53, pp. 55-72

Folk, R. L. and Land, R. S., 1975: Mg/Ca ratio and salinity: Two controls over crystallization of dolomite. A. A. P. G. Bull. 59, 60-69

Fortey, R. A., 1979: Early Ordovician trilobites from the Catoche Formation (St. George Group), western Newfoundland. in Contributions to Canadian paleontology. By T. E. Bolton, G. S. Nowlan, et al., Geol. Surv. Canada, Bulletin 321, 61-114

Gebelein, C. D. and Hoffman, P., 1973: Algal origin of dolomite laminations in stromatolitic limestone. J. Sed. Petrol., 43, 603- 613

Grover Jr., G. and Read, 1983.- Paleoacquifer and deep burial- related cements defined by reginal cathodoluminescence patterns, Middle Ordovician carbonates, Virginia. A.A.P.G. Bull .., 67, 1273-1303

Harris, L. D., 1973: Dolomitization model for Upper Cambrian and Lower Ordovician carbonate rocks in the eastern United States. Journal of Research, United States Geological Survey, 1: 63-78

Hem, J. D. , 1972: Cehemical factors that influence the availability of iron and manganese in aqueous systems. G. S. A. Bull., 83, 443- 450

James, N. P., Klappa, C. F., Skevington, D., and Stevens, R. K., 1980: Cambro-Ordovician of west Newfoundland, sediments and faunas. Geological Association of Canada, Field Trip Guidebook, Halifax, N. S.

Kastner, M., 1984: Control of dolomite formation. Nature, 311, 410-411

Kendall, A. C., 1977: Origin of dolomite mottling in Ordovician limestones from Saskatchewan and Manitoba. Bull. Can. Petrol. Geol., 25, 480-504

Klappa, C.F., Opalinski, P. R., and James, N. P., 1980: Middle Ordovician Table Head Group of western Newfoundland: a revised stratigraphy. Canadian Journal of Earth Sciences, 17: 1007-1019

Kluyver, H., 1975: Stratigraphy of the Ordovician St. George Group in the Port au Choix area, western Newfoundland. Canadian Journal of Earth Sciences, 12: 589-594

Knight, I. and Saltman, P., 1980: Platformal rocks and geology of the Roddickton Map area, Great Northern Peninsula, in: Report of Activities for 1979. Edited by C. F. O'Driscoll and R. V. Gibbons, Newfoundland Department of Mines and Energy, Report 80-1, pp. 10-28

Lasemi, Z. and Sandberg, P. A., 1984: Transformation of Aragonite- dominated lime muds to microcrystalline limestones. Geology, 12, 420-423

Lippman, F. , 1973: Sedimentary Carbonate Minerals, Springer-Verlag, Heidelberg, 228 p.

Logan, B. W., 1974: Inventory of Diagenesis in Holocene - Recent Carbonate Sediments, Shark Bay, Western Australia. in: Evolution and Diagenesis of Quaternary Carbonate Sequences, Shark Bay, Western Australia. A. A. P. G. Memoir 22, pp. 195-249

MaCauley, G. , 1987a, Organic geochemistry of some Cambro-ordovician outcrop samples, western Newfoundland. Geol. Surv. Canada, open file report 1503

MacQueen, R. W., and Powell, T. G., 1983: Organic geochemistry of the Pine Point lead-zinc ore field and region, Northwest Territories, Canada. Economic Geology, 78, pp. 1-25.

Mattes, B. W. and Mountjoy, E.W. , 1980: Burial dolomitization of the Upper Devonian Miette buildup, Jasper National Park, Alberta, in: D.H. Zenger et al., eds., Concepts and Models of Dolomitization, S. E. P. M., Spec. Pub. 28, 259-297

Mitra, S, 1988: Effects of deformation on reservoir potential in central Appalachian overthrust belt. Amer. Assoc. Petroleum Geologists, v. 72, no. 5, p. 536

Morrow, D. W. , 1978a: Dolomitization of Lower Pleozoic burrow fillings. J. Sed. Petrology, 48, 475-488

Nelson, S. J., 1955: Geology of Portland Creek - Port Saunders area, west coast. Nfld. Geol. Survey, Report 7, 1-57

Powell, T. G., and MacQueen, R. W., 1984: Precipitation of sulfide ores and organic matter: sulfate reactions at Pine Point, Canada. Science, 224, pp. 63-66

Pratt, B. R. , 1982a: Stromatolitic framework of carbonate mud mounds. Jour. Sedimentary Petrology, 52: 1203-1228

------ 1982b: Stromatolitic decline - a reconsideration. Geology. 10: 512-515

-------- and James, N. P., 1982: Cryptalgal -metazoan bioherms of Early Ordovician age in the St. George Group, western Newfoundland. Sedimentology, 29: 543-569

-------, 1986: The St. George Group (lower Ordovician) of western Newfoundland: tidal flat island model for carbonate sedimentation in shallow epeiric seas. Sedimentology, 33: 313-344

Smit, D. E. , 1981: Stratigraphy and sedimentary petrology of the Cambro-ordovician shelf sequence in western Newfoundland. Ph. D. thesis, University of Iowa, Iowa City, IA

Snow, G. and Knight, I., 1979: Geologic mapping of the carbonates of the Brig Bay map area, Newfoundland. Dept. Mines Energy, Mineral Devel. Div., Report 79-1, 1-6

Steinem, R. P., 1978: On the diagenesis of lime mud: SEM observations of subsurface material from Barbados. J. Sed. Petrol., 48, 1139-1148

-------- 1982: SEM observations on the replacement of Bahamian aragonitic mud by calcite. Geology, 10, 471-475

James, N. P., 1984: Shallowing-upward sequences in carbonates. In: Facies Models, R. G. Walker, ed. , Geoscience Canada, Reprint Series No. 1, pp. 213-228

Stouge, S. , 1980: Lower and Middle Ordovician conodonts from central Newfoundland and their correlatives in western Newfoundland. in: Current Research, Newfoundland Dept. Mines and Energy, Mineral Development Division, Report 80-1, 134-142

--------- 1982: Preliminary conodont biostratigraphy and correlation of Lower and Middle Ordovician carbonates of the St. George Group, Great Northern Peninsula, Newfoundland. Nfld. Dept. Mines and Energy, Mineral Development Division, Reort 82-3, 1-59

--------- 1983a: Notes on the geology of the Salmon River map area (12P/1), Great Northern Peninsula, Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division.

--------- 1983b, : Notes on the Geology of the St. Julien's map area (2M/4), Great Northern Peninsula, Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division.

--------- 1984: Conodonts of the Middle Ordovician Table Head Formation, western Newfoundland. Fossils and Strata, v. 16, 145 p

Tuke, M. F. , 1968: Autochthonous and allochthonous rocks of the Pistolet Bay area in northernmost Newfoundland. Cdn. Jour. Earth Sciences, 5, 501-522

Weaver, F. , 1983: Source rock studies of natural seep oils near Parsons Pond on the west coast of Newfoundland. Unpub. M-Sc. thesis, Memorial University of Newfoundland.

Williams, H., James, N. P., and Stevens, R. K., 1986: Humber Arm allochthon and nearby groups between Bonne Bay and Portland Creek, western Newfoundland. in Current Research, Part A, Geological Survey of Canada, Paper 85-1A. pp. 399-406

Williams, S. H., Boyce, W. D., and James, N. P., 1987: Graptolites from the Lower-Middle Ordovician St. George and Table Head Groups, western Newfoundland, and their correlation with trilobite, brachiopod and conodont zones. Cdn. Jour. Earth Sciences, 24, 456- 470

Woodward, H. H. , 1957: Geology of the Port Saunders - Castors River area, Newfoundland. Newfoundland Department of Mines and Resources, Geological Survey Report 10.

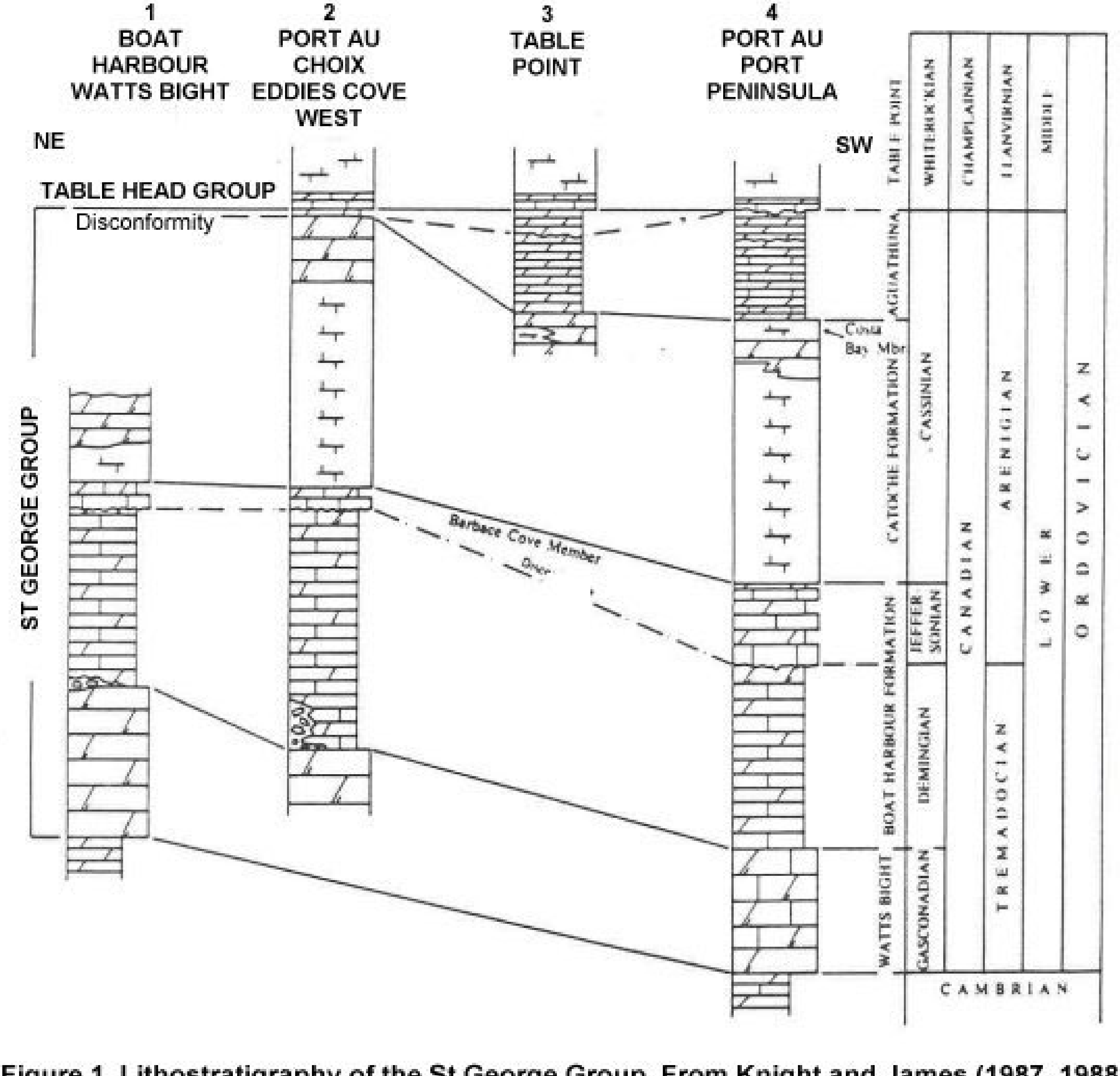

Figure 1. Lithostratigraphy of the St.George Group. From Knight and James (1987, 1988).