1

PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

PRECISIONSM RESOLUTION TARGETS

National Library
of Canada

Acquisitions and
Bibliographic Services Branch

395 Wellington Street
Ottawa, Ontario
K1A 0N4

Bibliothèque nationale
du Canada

Direction des acquisitions et
des services bibliographiques

395, rue Wellington
Ottawa (Ontario)
K1A 0N4

Your file - Votre référence

Our file - Notre référence

NOTICE

The quality of this microform is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Reproduction in full or in part of this microform is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30, and subsequent amendments.

AVIS

La qualité de cette microforme dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

La reproduction, même partielle, de cette microforme est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30, et ses amendements subséquents.

Canada

PETROGRAPHY, DIAGENESIS AND CARBONATE CEMENT GEOCHEMISTRY
ON THE SANDSTONES OF THE JURASSIC JEANNE D'ARC
FORMATION, JEANNE D'ARC BASIN, GRAND BANKS

by

BONNY WELSFORD, B.Sc.

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 Earth Science

Carleton University

Ottawa, Ontario

May 5, 1993

National Library
of Canada

Acquisitions and
Bibliographic Services Branch

395 Wellington Street
Ottawa, Ontario
K1A 0N4

Bibliothèque nationale
du Canada

Direction des acquisitions et
des services bibliographiques

395, rue Wellington
Ottawa (Ontario)
K1A 0N4

Your file Votre référence

Our file Notre référence

The author has granted an irrevocable non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of his/her thesis by any means and in any form or format, making this thesis available to interested persons.

L'auteur a accordé une licence irrévocable et non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de sa thèse de quelque manière et sous quelque forme que ce soit pour mettre des exemplaires de cette thèse à la disposition des personnes intéressées.

The author retains ownership of the copyright in his/her thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without his/her permission.

L'auteur conserve la propriété du droit d'auteur qui protège sa thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

ISBN 0-315-84171-0

Canada

Name

Earth Sciences - Geology

Dissertation Abstracts International is arranged by broad, general subject categories. Please select the one subject which most nearly describes the content of your dissertation. Enter the corresponding four-digit code in the spaces provided.

Earth Sciences - Geology

SUBJECT TERM

0372

SUBJECT CODE

U·M·I

Subject Categories

THE HUMANITIES AND SOCIAL SCIENCES

COMMUNICATIONS AND THE ARTS

Architecture 0729
Art History 0377
Cinema 0900
Dance 0378
Fine Arts 0357
Information Science 0723
Journalism 0391
Library Science 0399
Mass Communications 0708
Music 0413
Speech Communication 0459
Theater 0465

EDUCATION

General 0515
Administration 0514
Adult and Continuing 0516
Agricultural 0517
Art 0273
Bilingual and Multicultural 0282
Business 0688
Community College 0275
Curriculum and Instruction 0727
Early Childhood 0518
Elementary 0524
Finance 0277
Guidance and Counseling 0519
Health 0680
Higher 0745
History of 0520
Home Economics 0278
Industrial 0521
Language and Literature 0279
Mathematics 0280
Music 0522
Philosophy of 0598
Physical 0523

Psychology 0525
Reading 0535
Religious 0527
Sciences 0714
Secondary 0533
Social Sciences 0534
Sociology of 0340
Special 0529
Teacher Training 0530
Technology 0710
Tests and Measurements 0288
Vocational 0747

LANGUAGE, LITERATURE AND LINGUISTICS

Language 0679
General 0289
Ancient 0290
Linguistics 0291
Modern 0291
Literature 0401
General 0294
Classical 0295
Comparative 0297
Medieval 0298
Modern 0316
African 0591
American 0305
Asian 0352
Canadian (English) 0355
Canadian (French) 0355
English 0599
Germanic 0311
Latin American 0312
Middle Eastern 0315
Romance 0313
Slavic and East European 0314

PHILOSOPHY, RELIGION AND THEOLOGY

Philosophy 0422
Religion 0318
General 0321
Biblical Studies 0319
Clergy 0320
History of 0322
Philosophy of 0469
Theology 0323

SOCIAL SCIENCES

American Studies 0323
Anthropology 0324
Archaeology 0326
Cultural 0327
Physical 0310
Business Administration 0272
General 0770
Accounting 0454
Banking 0338
Management 0385
Marketing 0501
Canadian Studies 0503
Economics 0505
General 0508
Agricultural 0509
Commerce Business 0510
Finance 0511
History 0358
Labor 0366
Theory 0351
Folklore 0376
Geography 0366
Gerontology 0351
History 0376
General 0376

Ancient 0579
Medieval 0581
Modern 0582
Black 0328
African 0331
Asia, Australia and Oceania 0332
Canadian 0334
European 0335
Latin American 0336
Middle Eastern 0333
United States 0337
History of Science 0585
Law 0398
Political Science 0615
General 0616
International Law and Relations 0617
Public Administration 0814
Recreation 0452
Social Work 0626
Sociology 0627
General 0938
Criminology and Penology 0631
Demography 0624
Ethnic and Racial Studies 0624
Individual and Family Studies 0624
Industrial and Labor Relations 0624
Public and Social Welfare 0630
Social Structure and Development 0700
Theory and Methods 0344
Transportation 0709
Urban and Regional Planning 0999
Women's Studies 0451

THE SCIENCES AND ENGINEERING

BIOLOGICAL SCIENCES

Agriculture 0473
General 0285
Agronomy 0475
Animal Culture and Nutrition 0476
Animal Pathology 0359
Food Science and Technology 0478
Forestry and Wildlife 0479
Plant Culture 0480
Plant Pathology 0817
Plant Physiology 0777
Range Management 0746
Wood Technology 0306
Biology 0287
General 0308
Anatomy 0309
Biostatistics 0329
Botany 0353
Cell 0369
Ecology 0793
Entomology 0410
Genetics 0307
Limnology 0317
Microbiology 0416
Molecular 0433
Neuroscience 0821
Oceanography 0778
Physiology 0472
Radiation 0786
Veterinary Science 0760
Zoology 0760
Biophysics 0760
General 0760
Medical 0760

EARTH SCIENCES

Biogeochemistry 0425
Geochemistry 0996

Geodesy 0370
Geology 0272
Geophysics 0377
Hydrology 0386
Mineralogy 0411
Paleobotany 0345
Paleoecology 0426
Paleontology 0418
Paleozoology 0485
Palynology 0427
Physical Geography 0366
Physical Oceanography 0415

HEALTH AND ENVIRONMENTAL SCIENCES

Environmental Sciences 0748
Health Sciences 0566
General 0300
Audiology 0302
Chemotherapy 0567
Dentistry 0350
Education 0769
Hospital Management 0758
Human Development 0982
Immunology 0564
Medicine and Surgery 0347
Mental Health 0569
Nursing 0570
Nutrition 0380
Obstetrics and Gynecology 0354
Occupational Health and Therapy 0381
Ophthalmology 0571
Pathology 0572
Pharmacology 0382
Pharmacy 0573
Physical Therapy 0574
Public Health 0575
Radiology 0575
Recreation 0575

Speech Pathology 0460
Toxicology 0383
Home Economics 0386

PHYSICAL SCIENCES

Pure Sciences

Chemistry 0485
General 0749
Agricultural 0486
Analytical 0487
Biochemistry 0488
Inorganic 0738
Nuclear 0490
Organic 0491
Pharmaceutical 0494
Physical 0495
Polymer 0754
Radiation 0405
Mathematics 0605
Physics 0986
General 0606
Acoustics 0608
Astronomy and Astrophysics 0748
Atmospheric Science 0607
Atomic 0798
Electronics and Electricity 0759
Elementary Particles and High Energy 0609
Fluid and Plasma 0610
Molecular 0752
Nuclear 0756
Optics 0611
Radiation 0467
Solid State 0467
Statistics 0346
Applied Sciences 0984

Applied Sciences

Applied Mechanics 0346
Computer Science 0984

Engineering 0537
General 0538
Aerospace 0539
Agricultural 0540
Automotive 0541
Biomedical 0542
Chemical 0543
Civil 0544
Electronics and Electrical 0348
Heat and Thermodynamics 0545
Hydraulic 0546
Industrial 0547
Marine 0794
Materials Science 0548
Mechanical 0743
Metallurgy 0551
Mining 0552
Nuclear 0549
Packaging 0765
Petroleum 0554
Sanitary and Municipal 0790
System Science 0428
Geotechnology 0796
Operations Research 0795
Plastics Technology 0994
Textile Technology 0994

PSYCHOLOGY

General 0621
Behavioral 0384
Clinical 0622
Developmental 0620
Experimental 0623
Industrial 0624
Personality 0625
Physiological 0989
Psychobiology 0349
Psychometrics 0632
Social 0451

Carleton University
Ottawa, Canada K1S 5J7

1912-1992

Thesis contains black and white and/or coloured graphs/tables/photographs which when microfilmed may lose their significance. The hardcopy of the thesis is available upon request from Carleton University Library.

The undersigned recommend to the Faculty of Graduate Studies
and Research acceptance of the thesis

PETROGRAPHY, DIAGENESIS AND CARBONATE CEMENT GEOCHEMISTRY
ON THE SANDSTONES OF THE JURASSIC JEANNE D'ARC
FORMATION, JEANNE D'ARC BASIN, GRAND BANKS

submitted by Bonny Welsford, B.Sc.
in partial fulfilment of the requirements for
the degree of Master of Science

Thesis Supervisor

Chair, Department of Earth Science

Carleton University

June 4, 1993

Abstract

Detailed petrography of core samples from the Jurassic Jeanne d'Arc Formation and comparative material from sandstones of the overlying Cretaceous Hibernia Formation in the central portion of the Jeanne d'Arc Basin show them to be predominately quartz arenites and sublitharenites. The diagenetic sequence for the Jeanne d'Arc Formation includes early syntaxial quartz overgrowths and minor pyrite and later pore-filling and grain replacement by calcite and dolomite. Porosity reduction by physical compaction is strongly developed in places where early carbonate cementation was not pervasive. Evidence of mesogenetic dissolution includes contiguous regions of tightly cemented and porous sandstones, remnant poikilotopic patches of carbonate cement, framework grain dissolution, corroded grain boundaries and enlarged pores. Calcite, dolomite and ferroan dolomite cements are also characterized by different abundances of Mg, Fe, Sr, Mn, Na, $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$. $\delta^{13}\text{C}$ are slightly depleted with respect to the PDB standard, in part due to organically derived carbon. $\delta^{18}\text{O}$ values suggest pore waters derived from deeper shales likely influenced carbonatization and dissolution reactions in the Jeanne d'Arc Formation.

Acknowledgements

I would like to thank my thesis supervisor, Dr. R.W. Yole for his invaluable guidance and patience during the preparation of this thesis which undoubtedly improved the quality of the text.

The staff at the Canada-Newfoundland Offshore Petroleum Board, St John's and of the Canada Oil and Gas Lands Administration and Atlantic Geoscience Centre at the Bedford Institute of Oceanography, Dartmouth Nova Scotia are gratefully acknowledged for facilitating access to drill core and well data and for their helpful discussions of basin stratigraphy.

Chevron Resources Canada in Calgary and Bev Lane are gratefully acknowledged for facilitating in SEM (and EDX) analysis.

Partial funding through a Research Agreement to R.W. Yole by the Department of Energy, Mines and Resources is gratefully acknowledged.

I also would also like to extend my gratitude to John Loop at the University of Ottawa for his technical advice on trace element geochemistry, Peter Mustard for his petrographic help, Franz Nentwich for help in thin section preparation, Benoit Seguin for his drafting skills, Raymond Chamberland for his editing, Don Brown and Dr. Yole for collection of samples, Ron Conlon for his time and help in clay XRD and Doug Irwin for his moral support.

Finally I would like to thank my parents and my brother for their continued support.

Table of Contents

Abstract	iii
Acknowledgments	iv
Table of Contents	v
List of illustrations	
Tables	vii
Figures	viii
Plates	ix
Chapter 1: Introduction	
1.1 Objectives	1
1.2 Methods of Study	4
1.2.1 Petrographic Techniques	4
1.2.2 Geochemical Techniques	8
1.3 Previous Work	10
Chapter 2: Geological Setting of the Jeanne d'Arc Basin	
2.1 Tectonic Setting	11
2.2 Tectonic Evolution	11
2.3 Structural Elements of the Jeanne d'Arc Basin	15
2.4 Source Rocks	16
Chapter 3: Sandstone Petrography	
3.1 Textures	18
3.1.1 Grain Size	18
3.1.2 Sorting	21
3.1.3 Roundness and Sphericity	21
3.1.4 Packing	22
3.1.5 Sedimentary Structures	22
3.2 Mineralogical Composition	24
3.2.1 Detrital Composition	24
3.2.1.1 Quartz	33
3.2.1.2 Chert	36
3.2.1.3 Feldspar	36
3.2.1.4 Rock Fragments	38
3.2.2 Accessory Minerals	40
3.2.3 Carbonaceous Material	41
3.2.4 Fossils	41
3.2.5 Matrix	42
3.3 Authigenic Minerals	42
3.3.1 Quartz Overgrowths	42
3.3.2 Carbonate Cements	43
3.3.3 Clay Minerals	44
3.3.4 Pyrite	45
3.4 Porosity	46
3.5 Diagenetic Sequence	46

Chapter 4: Secondary Porosity Evolution	
4.1 Introduction	51
4.2 Primary Porosity	52
4.3 Porosity Reduction	53
4.3.1 Compaction	53
4.3.2 Cementation	61
4.4 Secondary Porosity	65
4.4.1 Types of Secondary Porosity	65
4.4.2 Solution Fronts.....	68
4.5 Mechanisms for Secondary Porosity Development	69
4.5.1 Shale Compaction	70
4.5.2 Organic Maturation	71
4.5.3 Aluminosilicate Dissolution	72
Chapter 5: Carbonate Cement Geochemistry of the Jeanne d'Arc and Hibernia Formations	
5.1 Introduction	74
5.2 Evaluation of Chemical Data	75
5.2.1 Major Elements: Calcium and Magnesium	80
5.2.2 Minor and Trace Elements	82
5.3 Fluid Composition	87
5.4 Stable Isotopes	89
5.4.1 Carbon Isotopes	91
5.4.2 Oxygen Isotopes	95
5.5 Chemical Constraints	95
5.6 Summary of Isotopic Data	97
Conclusions	100
Suggestions for Further Work	103
Plates	105
References	148
Appendix I: Sample Index	157
Appendix II: Probable Point Count Errors	161
Appendix III: Representative XRD Spectra	162

List of Tables

3.1	Textural Characteristics of Jeanne d'Arc Sandstones	19
3.2	Textural Characteristics of Hibernia Sandstones	20
3.3	Mineralogical Composition of Jeanne d'Arc Sandstones	26
3.4	Mineralogical Composition of Hibernia Sandstones	29
3.5	Detailed Mineralogy of Jeanne d'Arc Sandstones	30
5.1	a) Trace Element Geochemistry of the Jeanne d'Arc and Hibernia Formations using AAS	78
	b) Re-calculated Carbonate Cement Geochemistry	79
5.2	Equilibrium Concentrations of Cations in Fluids	88
5.3	Stable Isotope Analysis of Carbonate Cements from the Jeanne d'Arc and Hibernia Formations	90

List of Figures

1.1	Location of Mesozoic-Cenozoic Basins on the Grand Banks, (after Grant and McAlpine, 1990)	2
1.2	Structure, Sediment Thickness and Well Locations, Jeanne d'Arc Basin (after Grant and McAlpine, 1990)	3
2.1	Cross-section of the Jeanne d'Arc Basin (after Grant et al, 1986)	12
2.2	Jeanne d'Arc Basin Lithostratigraphy (after Grant and McAlpine, 1990)	14
3.1	Jeanne d'Arc Sandstone Classification Based on Ternary Diagram of Quartz, Feldspar and Rock Fragments (after Folk, 1974)	32
3.2	Percentage of Polycrystalline Quartz versus Mean Grain Size	35
3.3	Percentage Rock Fragments (metamorphic and sedimentary) versus Mean Grain Size	39
3.4	Diagenetic Sequence	47
4.1	Frequency Distribution: a) Total Present Porosity	55
	b) Pre-cement Porosity	55
4.2	Packing Proximity versus Depth	57
4.3	Compaction Curves a) Sclater-Christie Compaction Curve (1980)	59
	b) Sclater-Christie Curve for Depth Interval of Jeanne d'Arc Sandstones	59
	c) Jeanne d'Arc Compaction Plot (detrital grains)	60
	d) Jeanne d'Arc Compaction Plot (detrital grains + cement)	60
4.4	Relationship Between Cementation and Compaction	63
4.5	Carbonate Cements versus Total Porosity	64
5.1	Weight Percent CaCO ₃ and MgCO ₃	81
5.2	Relationship Between CaCO ₃ , MgCO ₃ , and FeCO ₃	83
5.3	Relationship Between Fe and Mn in Carbonate Cements	85
5.4	Stable Isotopic Composition of Hibernia and Jeanne d'Arc Cements	92
5.5	a) Sr/Ca versus $\delta^{18}O$	96
	b) Mn/Ca versus $\delta^{18}O$	96
5.6	Stable Isotopic Composition of Jeanne d'Arc Basin	98

Chapter 1: Introduction

The Jeanne d'Arc Basin of the eastern Grand Banks, offshore Newfoundland (Figure 1.1) is the site of most of the major oil discoveries off eastern Canada since discovery of the Hibernia oil field in 1979. This reflects a unique combination of rich oil-prone source rocks, thermal maturation histories, good reservoir beds, hydrocarbon trapping mechanisms and migration pathways. To date all hydrocarbon accumulations, including South Mara, Whiterose, Terra Nova, Ben Nevis, Hebron, Beothuk and Nautilus fields (Figure 1.2), occur in Upper Jurassic and Lower Cretaceous rift and rift-drift transition sandstones in a predictable geographic pattern (on or adjacent to a northwest trending trans-basin fault system) (Grant and McAlpine, 1990).

The Hibernia structure, a rollover anticline, ranks as the largest oil discovery on the eastern continental margin of North America. The recoverable oil reserves of this structure, located at the western end of the trans-basin fault trend are estimated to be between 79.5 to 127.2 x 10⁶ cubic meters (Grant and McAlpine, 1990). The Terra Nova structure, discovered in 1984 by Petro Canada and partners is a fault-dissected, northward-plunging anticline located on the faulted eastern flank of the basin, with testing on individual wells yielding oil up to 615.6 cubic meters per day (Grant and McAlpine, 1990). The main reservoir units penetrated in the basin are the Lower Cretaceous Hibernia, Ben Nevis and Avalon Formations and the Upper Jurassic Jeanne d'Arc Formation.

1.1 Objectives

The purpose of this study is to provide detailed petrographic

Figure 1.1: Mesozoic-Cenozoic basins (hachured areas) separated by positive tectonic elements (white areas) on the Grand Banks, offshore Newfoundland (after McAlpine, 1990). The basins represent a variety of tectonic styles from the wide basins to the northeast to the narrow, elongate basins to the south. Also shown is the 400 m bathymetric contour. The rectangular area surrounding the Jeanne d'Arc Basin is enlarged in Figure 1.2.

Figure 1.2 Diagrammatic representation of the structure, sediment thickness and well locations for the Jeanne d'Arc Basin (after Grant and McAlpine, 1990). The major positive tectonic elements include the Bonavista Platform to the west and the Outer Ridge Complex to the east. The wells in the study are underlined.

information augmented by geochemical data, for analysis of origin, diagenesis and reservoir properties of Jeanne d'Arc sandstones. Comparison with other sandstone reservoirs in the Jeanne d'Arc Basin, especially those of the Hibernia Formation, should greatly enhance the overall basin analysis.

The major objectives of the study are:

1. to determine the mineralogical composition (detrital and authigenic) and textural characteristics of sandstones in different reservoir zones and how these factors are related to diagenetic processes;
2. to establish the relative time of formation with respect to burial of authigenic components and determine the importance of their precipitation on the quality of the reservoir;
3. to examine secondary porosity development and distribution in relation to compaction, cementation and dissolution and consequent changes in reservoir quality during burial.
4. to use major, minor and trace element distributions and stable isotope data from carbonate cements to investigate possible sources and conditions of formation;
5. to compare reservoir properties and diagenetic histories of Hibernia and Jeanne d'Arc Formations.

1.2 Methods of Study

1.2.1 Petrographic

Logging of conventional core of the Jeanne d'Arc Formation from three Terra Nova wells (H-99, E-79 and C-09) carried out by the writer was supplemented with cores logged by D.M. Brown and R.W. Yole. Particular

attention was directed toward the occurrence of sedimentary structures, fossils, carbonate rich zones and dissolution features.

127 Jeanne d'Arc core samples from 7 Terra Nova oil field wells (K-07, K-08, I-97, H-99, K-18, E-79 and C-09) (sample index in Appendix I) and 14 stratigraphic equivalents in three other wells (West Ben Nevis B-75, Huskey Bow Valley Bonne Bay C-73 and Huskey Bow Valley Fortune G-57) were examined. In addition, 21 samples of the Hibernia Formation from three wells (South Mara C-13, Whiterose N-22 and J-49) east of the main Hibernia field were investigated. Three samples of the Catalina Formation from Terra Nova K-08 and I-97 and four samples of the West Ben Nevis Formation from West Ben Nevis B-75 were also studied, but are not treated in detail here.

To facilitate recognition and morphological characteristics of primary and secondary pores, 98 samples were impregnated with blue-dyed epoxy resin (Nentwich and Yole, 1991). Core slabs, approximately 4cm x 4cm x 0.5cm were immersed in a solution of 95% by volume of Coleman fuel and 5% methyl hydrate to remove crude oil and/or residual water, respectively. The procedure was repeated until no noticeable discoloration of the solution occurred. After heating on a hot plate at approximately 60 C for one hour, the samples were wrapped in polyethylene then aluminum foil (with pin holes punctured through both coatings to ensure solution penetration). The epoxy resin was prepared and the wrapped core slabs were soaked in progressively more concentrated acetone:epoxy mixtures ranging from 100% pure acetone to 80% epoxy to accomplish vapour exchange and epoxy penetration into pores.

Selected thin sections were stained for carbonate to identify

ferroan and non-ferroan calcites and dolomites using a procedure adapted from that outlined by Dixon (1965) and for feldspars using cobaltinitrate.

Petrographic investigation of the mineralogy of sandstones is based on point-counting 350 grains per thin section, using an automatic Swift Point Counter and a mechanical stage (Carver, 1976). A coarse grid was used to allow maximum coverage of the thin section and to ensure that the distance between grains exceeded the maximum grain size. The low compositional variability of Hibernia and Jeanne d'Arc sandstones did not warrant a larger number of point counts per thin section. After lengthy study, Nentwich (1980) determined the probable error as a function of the percentage of a component at the 75% confidence level for 350 point counts (and the results are shown graphically in Appendix 2). At a compositional percentage of 20%, the error at the 75% confidence level is $\pm 2.5\%$, indicating that three out of four analysis would give compositional percentages between 22.5% and 17.5%. Despite this recognized error associated with the compositional data, point count data are reported to one decimal point to show both the presence of minor framework grain components and their relative abundance with respect to one another.

Because of the generally well-sorted nature of the sandstones, statistical analysis of particle size distribution is based on counting 200 grains per thin section using a micrometer eyepiece. The apparent long axis of the detrital grain was recorded in mm and then converted to standard phi units. The mean and standard deviation (sorting) are calculated as outlined by Friedman and Sanders (1978). Two repeated measurements on 6 samples, one from each of the Terra Nova wells (except

TN-K-07) showed the reproducibility (precision) of the method was within acceptable limits (<1% to 4.2%).

Qualitative microscopic examination of the remaining core samples was pursued as dictated by the lithological character of the samples (conglomerates, siltstones and shales) and quality of prepared thin sections.

An average of 500 contacts per thin section between grains, grains and pore space and grains and authigenic constituents were counted for statistical study of variance of packing parameters (density and proximity) with depth (Kahn, 1956).

Thin sections containing contiguous regions of porous and tightly cemented sandstones were analyzed both independently with respect to one another and together to determine the petrographic characteristics of the cemented, porous and "bulk" (combined) parts of the thin section and to investigate the nature of the contact between them.

A Nuclide Luminoscope operating at 9-15 kV, 0.3-0.7 mA and approximately 0.05 Torr vacuum was used for cathodoluminescence study. Observations were made on thin sections to assist in the determination of origin (igneous, metamorphic or diagenetic) and characteristic features (overgrowths, pressure solution and impurities) of quartz varieties and in recognition of complex carbonate zonation (Zinkernagel, 1978). Variations in luminescence are interpreted as reflecting differences in (activator) Mn and/or (quencher) Fe content.

X-ray diffraction on a Phillips semi-automatic diffractometer was used to investigate clay minerals associated with each diagenetic stage. 5-10 mL of water was added to 5-7mg of powdered sample in a test tube,

gently agitated and placed in a sonic waterbath for two minutes to allow clay floccules (approximate size fraction) to aggregate before pipetting onto a glass slide and allowed to dry before being placed into a diffractometer. A Cu K alpha radiation source with settings at 20 mA, 40 kV and an aperture of divergence and scatter slits of 1° was used to scan samples at 2-36 two theta.

Selected samples were examined using a Cambridge Stereoscan 240 Scanning Electron Microscope operating at 20 kV and Kerex Delta 4 Energy Dispersive X-ray at Chevron Canada Resources Limited in Calgary to investigate unusual mineralogy, morphology of pore spaces, zonation in carbonate minerals and authigenic mineral sequences.

1.2.2 Geochemical Techniques

Atomic absorption spectroscopy using the Standard Curve Method (Angino and Billings 1967; Geochemistry Laboratory Manual, Ottawa University) was performed at Ottawa University. AAS was used to determine the chemical composition and diagenetic evolution of the carbonate cemented portion of several sandstone core samples. A selected group of 31 acid-leached sandstones were analyzed: 18 from the Jeanne d'Arc Formation and 13 from the Main Hibernia Zone of the Hibernia Formation.

25 mL of 6% (v/v) HCl (aq) was added to approximately one gram of air dried (bulk) samples and allowed to react several hours to ensure that all carbonate minerals were dissolved. The mixtures were then filtered with ashless Whatman 43 filter paper and washed with 6% (v/v) HCl (aq). The filtrate was collected and analyzed for Ca, Mg, Fe, Mn, Na and Sr. Lanthanum oxide and cesium chloride were added to samples to depress

Lanthanum oxide and cesium chloride were added to samples to depress inter-element interferences. In addition samples were analyzed for Al to determine if leaching of minerals occurred from the silicate portion of the core samples. The insoluble residue was ignited in a porcelain crucible at 600 C for two hours and the ashed residue was weighed. Elemental concentrations were normalized to 100% carbonate.

To obtain good precision it is necessary to control all parameters subject to variability such as solvents, flame, height of selection zone in the flame, feed rate, slit width and sample dilutions. The precision of the adopted method, determined by repeating the analyses of two samples and the KH2 and LMS-1 standards twice, was 4.9%, suggesting fairly good reproducibility. Apart from instrumentation, sample preparation and dilution may contribute to a loss in precision owing to the sensitivity of AAS. The least reliable results are for Na because of its low ionization potential (minimized by the addition of cesium chloride) and possible contamination during sample preparation and for Sr because sample solutions were diluted 121 times in order that the sample was within the optimum working range of the machine.

Accuracy was determined by comparing a reference standard with KH2 standard and was 3.5%.

Carbon and oxygen isotope ratios of carbonate cements were determined at the University of Ottawa by leaching of sandstone samples with anhydrous phosphoric acid at 25 C and analysis according to standard techniques (Land, 1990) in an attempt to estimate the temperatures of formation and source or sources of the carbonate cements. Precision of both the carbon and oxygen analyses is estimated at 0.1 permil.

1.3 Previous Work

Many aspects of the geology (Amoco Canada Petroleum Company Ltd., and Imperial Oil Limited., 1973; Sherwin, 1973; Jansa and Wade, 1975; Mckenzie 1980 and 1981; Arthur et al, 1982; McMillan, 1982; Beneteau and Sheppard, 1982; Handyside and Chipman 1983; Grant et al, 1986), tectonic evolution (Purcell, 1980; McMillan, 1982; Grant et al 1986; Memeley, 1986; Sinclair, 1988; Keen et al, 1987; Tankard and Welsink, 1987; Enachescu, 1987; Dwyer and Welsink, 1988; and Grant and McAlpine, 1990) and source rock geochemistry (Rashid et al, 1980; Swift and Williams, 1980; Powell, 1985; Avery et al, 1986; Grant et al, 1986; Creaney et al, 1987 and Grant and McAlpine, 1990) of the Grand Banks area and associated oil fields have been previously studied. Although the diagenetic history of the Hibernia sandstones (Brown, 1985; Abid, 1988; Brown et al, 1989) has been investigated in detail, the other reservoir sandstones including the Avalon, Ben Nevis, Catalina and Jeanne d'Arc sandstones have received relatively little attention to date. Two studies on carbonate cement geochemistry using stable isotopes concentrated on Hibernia (Abid, 1988) and Avalon sandstones (Hutcheon et al, 1985; Lee, 1987). The latter studies included examination of recrystallized fossil fragments and trace element analyses to augment isotopic data. Because there have been relatively few published studies of carbonate cement geochemistry in siliclastic rocks, the combination of trace element and isotope analysis in the Jeanne d'Arc Formation should not only provide clues to the origin and evolution of both the cements and the diagenetic fluids from which they were precipitated but also provide information about the relationship between secondary porosity development and burial diagenesis.

Chapter 2: Geological Setting of the Jeanne d'Arc Basin

2.1 Tectonic Setting

The tectonic evolution of the Jeanne d'Arc Basin is related to rifting and continental drift events which occurred during the sequential separation of North America from Europe from the Late Triassic (Amoco Canada Petroleum Company Ltd. and Imperial Oil Ltd., 1973; Keen et al, 1987; Tankard and Welsink, 1987) (Figure 2.1). The extensional terrane was further complicated by contemporaneous block faulting, vertical movement and erosion of the basement of metamorphic Precambrian rocks, Paleozoic metasediments and pre-rift igneous rocks (Enachescu, 1987).

2.2 Tectonic Evolution

The earliest rifting phase occurred on the northeastern continental margin of Canada in the Late Triassic-Early Jurassic with the Africa-North America plate break-up and initiation of seafloor spreading. Salt was deposited in an epicontinental sea between the Bonavista Platform and Flemish Cap (Enachescu, 1987). Salt flowage structures, including diapirs, pillows, turtle structures and rollover anticlines associated with listric normal faults and the tilting of fault blocks resulted in most of the structures that contain hydrocarbons in the Jeanne d'Arc Basin (Grant et al, 1986; Grant and McAlpine, 1990).

According to Grant and McAlpine (1990) this initial rifting phase was aborted north of the Newfoundland Fracture Zone along the southwest edge of the Grand Banks in the Early Jurassic. Epeirogenic subsidence occurred to the Late Jurassic and the Egret Member of the Rankin Formation

Figure 2.1 Axial and transverse geological cross-sections of the Jeanne d'Arc Basin, based on lines A-A' and B-B' shown in Figure 1.2 (after Grant et al, 1986). Hydrocarbon accumulations occur mainly in the Upper Jurassic-Lower Cretaceous synrift sediments. The Kimmeridgian source rock is shown by the black barred dot symbols.

(Figure 2.2) was deposited in a transgressive sequence. A deep sea formed off Nova Scotia, terminated to the north by the Iberian Peninsula and the Newfoundland Fracture Zone, resulting in a network of narrow seaways (Creaney et al, 1987; Powell, 1985). Combined with a period of high sea-level stand and maximum coastal onlap in the north Atlantic, the opportunity for dilution of source sediments by clastic debris and terrestrial organic matter was minimized (Powell, 1985). The Egret Member shales developed in a silled depression, the location of which was determined by the pre-existing rifts, formed at the initiation of seafloor spreading and resulting from pre-rift basement swelling between basins and the Tethys Ocean.

The second phase of rifting occurred during the late Jurassic (Tithonian) - Early Cretaceous (Early Valanginian) when Iberia separated from Northern Europe. Continent-continent transform motion along the Charlie Gibbs Fracture Zone, north of Orphan Knoll, was accompanied by east-west extension, block faulting and initiation of the Voyager and Egret basin-bounding faults (Keen et al. 1988; Sinclair, 1988) (Figure 2.2). The growth of salt anticlines occurred as source and reservoir rocks were deposited and the Hibernia structure was initiated as a rollover anticline onto the Murre Fault. The Avalon Uplift was elevated and pre-Cretaceous sediments were eroded and shed northward into the Jeanne d'Arc Basin (Jansa and Wade, 1975, Keen et al, 1987). The Outer Ridge Complex was also elevated and block-faulted which acted to isolate the basin from the northern portion of Flemish Pass and provided a secondary source of clastics (Grant et al, 1986; Sinclair, 1988).

Figure 2.2 Jeanne d'Arc Basin lithostratigraphy (after Grant and McAlpine, 1990).

North-south trending valleys cut into the Rankin Formation in the area of the Avalon Uplift and carried metaquartzite cobbles and other siliceous sediments northwards. These clastics were deposited as fluvial sandstones, conglomerates and shales of the Jeanne d'Arc Formation (Sinclair, 1988). Rapid progradation of the lower Member (Terra Nova) occurred as a result of renewed uplift, followed by transgression of the upper Beothuk Member (Sinclair, 1988). Tithonian-Berriasian shales of Fortune Bay Formation, marking the top of over-pressure zone overly the Jeanne d'Arc Formation.

Renewed uplift resulted in deltaic channels prograding across the southern part of the basin and depositing the Hibernia sandstones. The lower Hibernia zone received clastics from both the Avalon Uplift and Outer Ridge Complex (Sinclair, 1988). The lower Valanginian Upper Hibernia zone represents a second cycle of deltaic sedimentation (Sinclair, 1988).

The mid-Late Cretaceous was characterized by Labrador-Greenland rifting when northeast-southwest tensional stresses dominated and syn-sedimentary faults acted as conduits for hydrocarbon migration (Grant et al, 1986; Enachescu, 1987; Keen et al, 1987; Sinclair, 1988). This was followed by a transition from rifting to continental separation as incipient seafloor spreading and the formation of oceanic crust occurred between the Grand Banks and northern Europe (Grant and McAlpine, 1990).

2.3 Structural Elements of Jeanne d'Arc Basin

The Jeanne d'Arc Basin is associated with major crustal faults,

including the Late Triassic Murre Fault, which allowed for development of the initial rift valley and accounts for the majority of extension in the basin. It subsequently became the dominant listric bounding fault (west side of basin) (Keen et al, 1987).

The NNE-SSW Egret Fault and east-west Voyager Fault on the southeastern margin are two Cretaceous bounding faults that form natural boundaries of the basin (Enachescu, 1987). The Trave Fault is a major sedimentary fault which soles deeply at a low angle onto the Voyager Fault (Enachescu, 1987).

Secondary sedimentary faults, such as the NW-SE Ben Nevis Fault trend between Ben Nevis and Hibernia, form local grabens, horsts and tilted fault blocks, constituting excellent hydrocarbon traps (Enachescu, 1987).

Cross basin transfer faults, orthogonal to the normal basin forming faults, accommodated different amounts and rates of extension resulting in conspicuous offset patterns of the Jeanne d'Arc Basin (Dwyer, 1988).

2.4 Source Rocks

All hydrocarbons to date in the Jeanne d'Arc Basin are of one genetic family, geochemically typed to the oil-prone Kimmeridgian Egret Member shales of the Rankin Formation (Grant and McAlpine, 1990).

Avery et al (1986) and Grant and McAlpine examined organic maturation profiles and suggested that the thickness of the oil generating window was controlled by the structural configuration of the basin prior to the Late Cretaceous. Presently the oil window is thickest in the

Lower Cretaceous depocenter downdip of the trans-basin fault trend.

An overpressure zone occurs from the base of the Egret Member to the top of the Fortune Bay Formation and is related to an increase in shale porosity due to the inability of interstitial fluids to escape freely, leading to undercompaction. Undercompaction may be a result of sediment load increasing too rapidly in the Jeanne d'Arc Basin, and likely occurred during the initial phase of the second period of rift subsidence. Preliminary studies show evidence of a break in the rate of smectite-illite transformation in clays associated with the top of the overpressure zone and this retardation in clay diagenesis may have resulted from the lack of dewatering in undercompacted zones (caused by rapid burial) Grant and McAlpine (1990).

Chapter 3: Sandstone Petrography

3.1 Textures

Grain size analysis of Jeanne d'Arc sandstones indicate that sandstones are texturally mature, predominantly medium to coarse-grained, sub-angular to sub-rounded, highly spherical and moderately well sorted (Tables 3.1 and 3.2).

3.1.1 Grain Size

Approximately 200 grains per thin section were measured (apparent long axes) and the average calculated for mean apparent grain size.

The Jeanne d'Arc Formation is characterized by very fine to coarse grained sandstones with the most frequently occurring particle size falling within the medium-grained (+1 to +2 phi) sand class. In contrast, samples selected from wells outside of the main Hibernia field penetrating the Hibernia Formation are very fine grained and moderately well sorted. These Hibernia sandstones differ texturally from the sandstones within the main field (previous studies, e.g. Brown, 1985).

Probability plots of cumulative frequency distributions for the Jeanne d'Arc Formation (not included in this study) suggest the sandstones are polymodal (presence of multiple straight line segments) whereas Hibernia distributions are unimodal. This pattern supports the theory that coarser modes (developing as a result of drastic changes in energy levels, sediment sources and/or grain characteristics of particles available for deposition) tend towards polymodality and finer modes tend towards unimodality (Dias and Neal, 1990).

Table 3.1: Textural Characteristics of Jeanne d'Arc Sandstones

Sample	Depth (m)	Round.	Spher.	Mean (phi)	Std dev. (phi)	Sample	Depth (m)	Round.	Spher.	Mean (phi)	Std dev. (phi)
TN-N-99-1-1	3227.70	A-sr	0.7-0.9	1.5	0.6	TN-K-07-2	3327.80	sr	0.7-0.9	2.0	0.5
TN-N-99-1-2 ^a p	3228.59	sr-R	0.5-0.7	1.4	0.8	TN-K-07-3	3329.40	sr-sa	0.5-0.7	0.7	0.8
TN-N-99-1-2 ^a c	3228.59	sr-R	0.5-0.7	1.4	0.9	TN-K-07-4	3334.40	sa-sr	0.9	1.5	0.7
TN-N-99-1-4	3233.78	sa-sr	0.7-0.9	1.5	0.7	TN-K-07-5	3338.10	sa-sr	0.5-0.7	0.9	0.8
TN-N-99-2-5	3240.07	sa	0.5	1.6	0.6	TN-K-07-6	3339.80	sa-sr	0.7-0.9	0.4	0.8
TN-N-99-2-6 ^a p	3241.57	sa-sr	0.7-0.9	2.9	0.8	TN-K-07-8	3355.05	sa-A	0.7	1.7	1.1
TN-N-99-2-6 ^a c	3241.57	sa-sr	0.7-0.9	3.1	0.7	TN-K-07-9	3358.50	sr-R	0.9	1.6	0.4
TN-N-99-2-7 ^a p	3243.23	sa-sr	0.7-0.9	1.3	0.6	TN-K-07-10	3365.01	sa-sr	0.7-0.9	0.4	1.4
TN-N-99-2-8	3247.25	sa-sr	0.5-0.7	0.7	0.7	TN-K-07-11	3366.50	sr-R	0.7-0.9	1.2	0.8
TN-N-99-3-9	3254.84	sa-sr	0.9	1.8	0.5						
TN-N-99-3-10	3260.68	sr-R	0.7-0.9	0.3	0.7						
TN-N-99-3-11 ^a p	3261.13	sr	0.7-0.9	0.9	0.7						
TN-N-99-3-12	3263.42	sr-R	0.7-0.9	1.1	0.5						
TN-N-99-4-13	3268.87	R	0.7-0.9	1.4	1.0						
TN-N-99-4-14	3269.37	sa-sr	0.7	2.2	0.6						
						TN-K-18-1-1	3204.42	sr-R	0.9	2.0	0.5
TN-1-97-2 ^a (C)	3268.00	A-sa	0.5-0.7	3.5	0.5	TN-K-18-2-1	3218.37	A-sa	0.7-0.9	0.5	0.6
TN-1-97-2-1	3302.08	sa-sr	0.5-0.7	1.6	0.5	TN-K-18-2-2	3221.90	A-sr	0.5-0.7	2.3	0.6
TN-1-97-3	3304.00	sa-R	0.5-0.7	1.6	0.6	TN-K-18-3-1	3235.65	sa-R	0.7-0.9	2.4	0.6
TN-1-97-4	3304.50	sa-A	0.7	1.9	0.6	TN-K-18-2	3242.75	sa-sr	0.7-0.9	2.9	0.5
TN-1-97-2-2	3305.00	sa-sr	0.7-0.9	1.4	0.5	TN-K-18-4-1	3248.96	sa-R	0.9	2.6	0.4
TN-1-97-5	3311.30	A-sr	0.5-0.7	0.9	0.6	TN-K-18-4-2	3254.60	sr	0.9	1.9	0.5
TN-1-97-3-1	3312.03	sr	0.7	0.5	0.7						
TN-1-97-3-2	3312.44	sa	0.7	2.8	0.6						
TN-1-97-6	3312.70	sa-sr	0.5-0.7	0.4	0.6						
TN-1-97-4-1	3314.95	sr-R	0.7-0.9	0.8	0.6						
TN-1-97-8	3315.60	sr-R	0.5-0.7	0.2	0.5						
TN-1-97-4-2	3317.86	sa-sr	0.7-0.9	1.4	0.5						
TN-1-97-9	3318.80	sa-sr	0.5-0.7	2.1	0.5						
TN-1-97-5-1 ^a p	3319.80	sr	0.9	1.5	0.5						
TN-1-97-5-1 ^a c	3319.80	sr	0.9	1.1	0.6						
TN-1-97-10	3323.28	A-sa	0.7	0.9	0.9						
TN-1-97-11	3324.30	sa-A	0.5-0.7	0.8	0.7						
TN-1-97-5-2	3324.55	sa-sr	0.7-0.9	1.3	0.9						
TN-1-97-6-1 ^a p	3326.00	sa-sr	0.5-0.7	1.1	0.6						
TN-1-97-12	3326.00	sr	0.7	1.2	0.9						
TN-1-97-7-2	3327.47	A-sr	0.7	1.0	0.9						

^adenotes contact between carbonate cemented area and porous sandstone^asame as above, bulk rock analysed

Table 3.2: Textural Characteristics of Hibernia Sandstones

Sample	Depth (m)	Round.	Spher.	Mean (phi)	Std. Dev. (phi)
SM-C-13-1	4392.52	SA-sR	0.7-0.9	3.0	0.5
SM-C-13-5-1	4355.30	SA-sR	0.7-0.9	3.3	0.5
SM-C-13-5-2	4396.46	SA-sR	0.7-0.9	3.1	0.5
SM-C-13-2	4400.50	SA-sR	0.7-0.9	4.2	0.7
SM-C-13-6-1	4582.90	sR	0.9	3.7	0.6
SM-C-13-6-2	4585.33	sR	0.9	3.9	0.5
SM-C-13-3	4586.84	SA-sR	0.7-0.9	3.6	0.5
SM-C-13-4	4588.29	SA	0.9	3.6	0.5
WR-N-22-1	3378.80	sR-R	0.9	4.2	0.6
WR-N-22-2	3392.50	SA-sR	0.7-0.9	3.8	0.6
WR-N-22-3	3565.40	SA-sR	0.7-0.9	3.0	0.6
WR-N-22-2-1	3566.27	sR	0.7-0.9	2.8	0.5
WR-N-22-4	3566.80	SA-sR	0.7	2.9	0.5
WR-N-22-2-2	3568.87	SA-sR	0.7-0.9	3.1	0.6
WR-N-22-5 *c	3569.22	sR	0.7-0.9	3.0	0.5
WR-N-22-5 *p	3569.22	sR	0.7-0.9	3.0	0.6
WR-N-22-3-1	3570.20	sR	0.7-0.9	3.4	0.5
WR-N-22-3-2	3572.70	SA	0.5-0.7	3.6	0.6
WR-N-22-6	3573.00	SA-sR	0.7-0.9	3.6	0.5
WR-J-49-1 *c	3916.10	SA-sR	0.7	3.2	0.5
WR-J-49-1 *p	3916.10	SA-sR	0.7	3.2	0.5
WR-J-49-2	3920.50	sR-R	0.9	3.2	0.4
** WBN-B-75-1 *c	2088.10	SA	0.5-0.7	3.1	0.5
** WBN-B-75-1 *p	2088.10	SA	0.5-0.7	3.4	0.6
** WBN-B-75-2	2094.20	SA	0.9	3.3	0.6
** WBN-B-75-5	2062.60	SA-sR	0.7	3.5	0.5

*denotes contact between carbonate cemented area and porous ss

**Lower Cretaceous Ben Mevis sandstones

3.1.2 Sorting

Petrographic studies indicate that the Jeanne d'Arc sandstones are commonly moderately well sorted with a range in standard deviation of 0.38 phi to 1.357 phi, whereas Hibernia samples tend to be moderately well to well sorted with a range in standard deviation of 0.44 phi to 0.63 phi.

3.1.3 Roundness and Sphericity

The roundness of quartz grains in samples was visually estimated by matching the outlines of individual particles with diagrams of two sets of standard sand particles each having different sphericity (Powers, 1953). Monocrystalline quartz in Jeanne d'Arc sandstones vary from angular to subrounded with a predominance of sub-angular to sub-rounded grains. Rounding appears to decrease with size and increase with depth. Hibernia quartz grains of this study are more angular because of their finer grain size and there is no obvious correlation between roundness and vertical/lateral stratigraphic position.

Diagenetic modifications to the shapes of detrital quartz grains, such as secondary enlargement by silica cementation, partial replacement by carbonate cements or subsequent corrosion of quartz grain boundaries by the dissolution of the carbonate cements may create problems in determining primary shapes of the sand grains. As all of these features are evident, roundness estimates are minimums.

Most feldspars and rock fragments are less well rounded than quartz grains. Chert, however is often more well rounded than associated quartz in Jeanne d'Arc samples.

Sphericity, visually estimated from grain images of Powers (1953) is

moderately high to high (0.7 to 0.9) in Jeanne d'Arc sandstones. Hibernia sandstones of this study have low to high sphericities (0.5 to 0.9).

3.1.4 Packing

Packing of grains may be quantified from individual samples studied in thin section using a technique developed by Kahn (1956). Approximately 500 contacts between grains, grain and pore space and grains and cement were counted per thin section for 55 samples. Packing proximity is the ratio of the number of grain-to-grain contacts to the total number of contacts and packing density refers to how closely the grains are packed. The two parameters are interdependent and closely related to diagenetic processes. Results will be discussed in Chapter 4.

Grain contact characteristics vary depending on composition and depth (diagenesis). Grain contacts tend to be straight or concavo-convex in those sandstones with relatively abundant ductile rock fragments, whereas point contacts are more prevalent where secondary porosity is high (Plate 1) because of early cementation and inhibition of physical compaction. Sandstones that are characterized by poikilitopic cement show relatively high proportion of floating grains.

Inhomogeneous packing is common in both formations studied and is prominent in areas that have been affected by early cementation adjacent to areas that have been affected by mechanical compaction.

3.1.5 Sedimentary Structures

Bedding planes between individual sandstone units are commonly obscure, whereas compositional breaks between sandstones and shales,

shales and conglomerates and conglomerates and sandstones are abrupt (Plate 2).

Trough cross-bedding and planar cross-bedding occur throughout most of the Jeanne d'Arc sequence, with the former typical in finer-grained sandstones. Subhorizontal laminae, planar cross bedding and ripple laminae are also common in shaly, silty shale and siltstone samples (Plates 1). Parallel horizontal laminae are more common than low angle cross bedding (Plates 2).

Discontinuous shaly laminae (Plate 3) and flattened ovoid mud-rip up clasts (Plate 3) suggesting ductile deformation during burial was common. Siderite nodules are common in both sandstones and shale sequences (Plates 4) and are rare in conglomerate beds. The nodules vary in size from less than 0.5 cm to as large as 4.5 cm and are typically irregularly-shaped and elongate parallel to bedding, possibly suggesting that they were not well indurated during burial.

The contact between tightly carbonate-cemented sandstones and more porous sandstones may be gradual, sharp or abrupt and laterally or vertically discontinuous (Plates 4, 5, and 6).

Bioturbation (Plate 6) is rare with burrowing the dominant form. Visible burrows are concentrated in zones of interlaminated rippled sandstone and shales. The effect of bioturbation on microfabric is observed in thin sections where burrowing has disrupted silt laminae and has altered evidence of the original fabric. Macroscopically bioturbation results in mottling. In extreme cases it alters the physical structure of silty shales by partial or complete homogenization, with the latter mimicking uniform deposition.

The most common macroscopic feature observed in shales between sandstones is horizontal lamination, usually with silty laminae showing normal grading with both gradational and abrupt contacts. Other structures recognized in the shales include slickenside, micro-cross-lamination (Plate 7) and soft sediment deformation features such as load structures, syn-sedimentary faults and folds, convolute (Plate 6) and wavy bedding and slumping.

Two types of conglomerates are present in the Jeanne d'Arc sequence: polymictic, poorly sorted, matrix-supported conglomerate (Plate 7) and moderately to poorly sorted framework supported polymictic conglomerates. In framework supported conglomerates, dissolution along grain margins, vuggy porosity, vertical, unhealed and partially mineralized fractures cutting through grains and matrix, intensely fractured grains, and calcite veins are common.

3.2 Mineralogical Composition

Detailed logging of conventional core from the Jurassic Jeanne d'Arc and the Cretaceous Hibernia Formations provided 146 sandstone samples for petrographic investigation. Preference was given to samples which best represented the section from which they were derived. This allowed a reasonable assessment of mineralogy, texture, depositional environments and diagenetic processes which contributed to the overall geological history of the sandstone successions.

3.2.1 Detrital Composition

Thin sections were point-counted for detrital grains, authigenic minerals, matrix and porosity types. (Framework grains were recalculated

to 100% of the detrital component). The results for Jeanne d'Arc and Hibernia sandstones are shown in Tables 3.3 and 3.4, respectively. Detailed subdivisions for polycrystalline quartz, feldspars, lithic fragments, carbonate cements and porosity were made in an attempt to better characterize the reservoir units and are recorded in Table 3.5.

As mentioned earlier in Chapter 1, the error associated with point counting 350 grains ranges from about 2.9% to less than 0.5% at the 75% confidence level. This uncertainty is larger than the detection limits for the lowest abundant components. Therefore the data may not be a reflection of absolute percentages of constituents but rather an indication of the relative abundance of the observed component with respect to the total sandstone composition. Errors associated with point count analysis of the Jeanne d'Arc and Hibernia sandstones include the difficulty in separating very fine silt-size quartz grains, especially in fine-grained sandstones and ductile sedimentary rock fragments from matrix, identifying quartz overgrowths in the absence of dust rims or impurities, distinguishing ferroan calcite and dolomite (both stain blue), obtaining reasonable coverage of the thin section such that the presence of trace and minor components are accurately documented without bias, distinguishing between preserved primary porosity and secondary pores and differentiating chert and siliceous rock fragments.

A distinctive feature of both Hibernia and Jeanne d'Arc sandstones is their simple detrital composition, consisting of quartz, lithic fragments, chert and feldspars. Most sandstones studied are compositionally mature, plotting as sublitharenites or quartz arenites (Folk, 1974) (Figure 3.1). Only five Jeanne d'Arc sandstones plot as subarkoses. Most of the

Table 3.3: Mineralogical Composition of Jeanne d'Arc Sandstones

Sample	Depth (m)	Det	Recal to 100%							Auth						
			Qm	Op	Ch	Fsp	SRF	MRF	Si	Ca	Py	Cy	Cm	M	Por.	
TN-H-99-1-1	3227.70	66.0	81.4	10.4	3.0	3.0	1.3	0.9	2.3	5.4	0.3	1.4	-	2.6	22.0	
TN-H-99-1-2 *c	3228.59	73.4	82.5	11.7	1.2	0.8	3.1	0.8	3.7	15.4	3.1	2.9	0.6	-	0.9	
TN-H-99-1-2 *p	3228.59	68.0	78.2	13.9	2.9	0.8	3.4	0.8	3.1	8.3	3.1	1.4	-	-	16.0	
TN-H-99-1-3 **	3229.95	62.9	74.6	12.7	5.0	2.3	3.2	2.3	1.1	16.9	0.6	0.6	1.1	1.7	15.1	
TN-H-99-1-4	3233.78	66.9	79.5	12.0	3.9	3.0	1.3	0.4	2.3	2.9	-	2.6	1.7	1.7	22.0	
TN-H-99-2-5	3240.07	68.0	79.4	12.6	2.9	2.9	2.1	-	2.6	4.9	0.9	1.4	0.6	4.3	17.4	
TN-H-99-2-6 *c	3241.57	69.7	86.5	7.8	1.6	1.6	2.5	-	3.7	22.6	0.6	1.7	-	-	1.7	
TN-H-99-2-6 *p	3241.57	68.6	85.0	8.3	2.1	0.8	3.8	-	2.6	8.0	1.1	1.7	-	-	18.0	
TN-H-99-2-7 **	3243.45	69.1	76.2	13.1	2.9	1.6	4.9	1.2	2.3	22.9	0.6	0.6	-	2.0	2.6	
TN-H-99-2-8	3247.25	74.0	74.1	10.0	5.8	1.5	5.6	1.9	2.0	5.4	2.3	1.1	-	1.7	13.4	
TN-H-99-3-9	3254.84	67.7	84.5	11.7	1.7	2.1	-	-	2.3	4.3	0.3	1.1	-	0.3	24.0	
TN-H-99-3-10	3260.68	72.6	75.7	15.7	2.8	1.2	3.1	1.6	1.1	23.1	0.6	0.6	-	-	2.0	
TN-H-99-3-11 **	3261.15	77.1	68.3	20.7	3.3	1.5	4.4	1.9	0.0	18.6	0.3	0.9	0.6	1.1	1.4	
TN-H-99-3-12	3263.42	79.4	78.1	14.4	2.9	1.8	2.2	0.7	2.6	14.6	0.6	1.7	-	-	1.1	
TN-H-99-4-13	3268.87	82.9	79.0	12.4	4.1	0.7	2.8	0.7	2.3	13.7	0.6	-	0.6	-	-	
TN-H-99-4-14	3269.37	70.9	89.1	5.2	2.0	3.2	0.4	-	4.0	8.6	3.4	0.6	-	-	12.6	
TN-I-97-2 * (C)	2368.00	67.4	90.7	2.5	3.4	3.4	-	-	1.7	20.0	0.6	1.4	3.1	-	5.7	
TN-I-97-2-1	3302.08	69.2	82.3	10.3	3.3	0.6	2.5	0.8	2.6	8.3	4.3	1.4	-	2.0	12.3	
TN-I-97-3	3304.00	61.2	78.1	11.2	1.9	4.7	2.8	1.4	3.7	10.0	1.1	0.6	-	-	23.4	
TN-I-97-4	3304.50	67.4	84.3	6.8	0.8	3.8	3.4	0.8	4.0	0.6	7.4	3.1	-	-	17.4	
TN-I-97-2-2	3305.00	74.6	82.4	11.1	1.5	0.8	3.1	1.2	1.7	1.1	4.6	-	0.9	-	17.1	
TN-I-97-5	3311.30	74.6	81.2	9.6	3.8	1.2	3.1	1.2	1.4	21.4	0.3	-	0.9	-	1.4	
TN-I-97-3-1	3312.03	63.4	74.4	16.4	4.1	0.9	3.2	0.9	0.3	12.9	0.6	-	0.3	0.9	22.6	
TN-I-97-3-2	3312.44	80.3	89.3	4.6	2.9	1.8	1.1	0.4	3.4	0.9	1.1	0.6	-	0.9	12.9	
TN-I-97-6	3312.70	68.0	77.3	10.4	4.2	1.3	2.1	0.8	1.7	27.7	0.6	0.6	1.1	-	0.9	
TN-I-97-4-1	3314.75	71.4	73.2	16.8	4.4	2.8	2.0	0.8	3.1	22.6	0.9	-	-	-	2.0	
TN-I-97-8	3315.60	68.6	72.9	19.2	3.3	0.8	2.1	1.1	1.4	23.1	1.7	0.9	0.3	-	4.0	
TN-I-97-4-2	3317.86	74.6	75.9	13.8	5.7	1.2	3.1	0.4	2.0	6.3	2.3	1.7	1.1	-	12.0	
TN-I-97-5-1 *p	3314.80	78.0	80.3	11.2	3.9	2.3	0.8	0.8	1.8	3.9	1.2	0.3	-	-	14.8	

Abbreviations

Det:	percentage detrital composition of bulk sample
Qm:	monocrystalline quartz
Qp:	polycrystalline quartz
Ch:	chert
Fsp:	feldspar
SRF:	sedimentary rock fragment
MRF:	metamorphic rock fragment
Si:	silica cement (quartz overgrowths)
Ca:	carbonate cement (calcite and dolomite)
Py:	pyrite
Cy:	clay minerals
Cm:	carbonaceous material
M:	matrix
Por:	porosity (primary and secondary)

Table 3.3: Mineralogical Composition of Jeanne d'Arc Sandstones (...continued)

Sample	Depth (m)	Det	Recal to 100%							Auth					N	Por.
			Om	Op	Ch	Fsp	SRF	RRF	Si	Ca	Py	Cy	Om			
TN-I-97-5-1 *p	3314.80	78.0	80.3	11.2	3.9	2.3	0.8	0.8	1.8	3.9	1.2	0.3	-	-	-	14.8
TN-I-97-5-1 *c	3314.80	77.7	85.7	9.2	1.8	1.8	1.1	0.7	1.1	15.1	1.1	0.6	-	-	-	4.3
TN-I-97-9	3318.80	68.6	81.3	9.2	2.1	3.3	3.3	0.8	4.3	3.4	8.6	1.1	-	0.9	-	13.1
TN-I-97-10	3323.20	76.6	74.3	17.5	3.0	6.8	4.1	0.4	2.3	18.3	1.7	1.1	-	-	-	-
TN-I-97-11	3324.30	72.0	77.0	15.9	2.0	0.8	3.6	0.8	4.0	13.4	0.6	1.1	-	-	-	8.9
TN-I-97-5-2	3324.55	76.6	79.1	11.9	3.7	0.8	3.0	1.5	3.4	5.1	1.1	0.9	3.7	-	-	9.1
TN-I-97-6-1 **	3326.00	70.6	82.1	13.4	1.6	0.8	1.6	0.4	1.1	22.9	4.0	0.3	0.6	-	-	0.6
TN-I-97-12	3326.00	64.3	84.0	11.6	2.7	0.9	0.9	-	0.6	26.6	1.1	2.6	-	-	-	4.9
TN-I-97-13	3326.50	58.0	80.8	12.8	2.0	1.0	2.5	1.0	4.0	20.6	0.9	2.9	-	-	-	13.7
TN-I-97-14	3326.80	69.2	87.6	8.3	1.2	1.2	0.8	0.8	4.6	3.7	-	2.9	0.6	4.6	-	14.6
TN-I-97-7-2	3327.47	68.6	69.2	20.0	2.5	2.5	4.2	1.7	6.6	1.1	0.9	2.3	1.1	-	-	19.4
TN-I-97-15	3327.70	68.9	85.1	7.9	2.1	2.9	1.2	0.8	7.1	1.4	0.6	2.0	3.4	3.1	-	13.4
TN-K-07-1 ***	3327.10	80.0	90.0	8.0	1.0	1.0	-	-	1.0	15.0	1.0	1.0	1.0	-	-	1.0
TN-K-07-2	3327.80	70.3	83.7	8.1	0.8	1.2	4.1	2.0	5.1	0.3	0.6	0.9	-	0.3	-	22.6
TN-K-07-3	3329.40	74.3	71.2	16.9	3.9	3.9	3.9	0.4	1.4	10.3	1.1	0.3	-	1.4	-	11.1
TN-K-07-4	3334.40	73.2	82.8	8.2	1.2	3.1	3.5	1.2	6.9	1.1	-	1.1	-	-	-	17.7
TN-K-07-5	3338.10	62.2	80.6	11.1	6.0	1.8	0.5	-	2.9	28.0	3.4	-	2.6	-	-	0.9
TN-K-07-6	3339.80	69.7	76.2	13.9	4.5	2.1	2.1	1.2	2.0	22.6	2.0	1.4	-	-	-	2.3
TN-K-07-8	3355.05	77.2	83.7	7.8	0.4	3.3	4.4	0.4	2.0	-	3.7	1.7	1.1	-	-	14.3
TN-K-07-9	3358.50	62.6	78.1	13.2	0.9	5.0	1.4	1.4	1.4	9.7	0.3	4.0	-	4.3	-	17.7
TN-K-07-10	3365.01	78.7	69.5	17.0	5.5	2.1	5.1	0.9	2.3	16.7	1.0	0.3	-	-	-	1.0
TN-K-07-11	3366.30	73.7	82.2	13.2	1.9	1.2	0.8	0.8	2.6	19.7	2.9	-	0.6	-	-	0.6
TN-K-18-1-1	~204.32	65.1	83.8	14.0	0.9	0.9	-	0.4	2.3	3.1	1.7	1.4	1.4	-	-	24.9
TN-K-18-1	3204.80	75.0	80.0	7.5	4.0	1.0	5.5	2.0	5.0	15.0	1.0	1.0	-	2.0	-	1.0
TN-K-18-2-1	3218.37	73.7	77.1	15.5	3.1	0.8	2.3	1.2	1.1	20.3	1.4	1.4	0.6	-	-	1.4
TN-K-18-2-2	3221.90	71.4	85.9	7.3	2.4	2.0	2.4	-	0.6	25.7	0.9	0.3	0.6	0.6	-	-
TN-K-18-3-1	3235.65	82.9	82.4	7.6	4.1	2.4	3.1	0.3	1.4	14.9	0.6	0.3	-	-	-	-
TN-K-18-2	3242.75	79.7	90.3	5.0	2.9	0.4	1.4	-	2.6	9.7	1.1	1.7	1.1	1.1	-	2.9

Table 3.3: Mineralogical Composition of Jeanne d'Arc Sandstones (...continued)

Sample	Depth (m)	Det	Recal to 100%							Auth						
			Qm	Op	Ch	Fsp	SRF	HRF	Si	Ca	Py	Cy	Om	M	Por.	
TN-K-18-4-1	3248.96	62.9	75.0	16.4	0.5	5.5	2.3	0.5	7.1	6.9	1.1	2.3	1.4	2.0	16.3	
TN-K-18-4-2	3254.60	76.9	81.4	11.5	3.3	1.2	2.6	-	4.9	12.3	3.4	0.6	-	-	2.0	
TN-K-18-3	3256.50	78.6	86.2	9.1	1.1	1.1	2.6	-	4.3	11.4	0.9	0.9	-	3.1	0.9	
TN-K-18-6-1	3262.25	82.9	92.8	2.8	3.1	0.7	0.7	-	1.7	6.9	0.3	1.1	-	-	7.1	
TN-K-18-4	3262.40	72.6	82.7	7.1	5.5	1.2	3.2	0.4	1.6	25.1	-	0.6	-	-	0.6	
TN-K-18-6-2	3262.60	82.0	92.7	5.6	0.7	0.7	0.4	-	1.4	16.3	0.3	-	-	-	-	
TN-K-18-5	3264.30	80.9	81.3	13.4	1.8	0.3	2.5	0.7	2.3	14.9	-	0.6	-	-	1.4	
TN-K-18-6	3265.60	78.3	64.0	24.3	5.9	0.7	4.0	1.1	1.2	17.7	1.7	0.3	0.9	-	-	
TN-K-18-7-1	3266.00	72.9	87.7	7.1	2.8	1.6	0.8	-	4.9	8.6	0.3	2.0	-	-	11.4	
TN-K-18-7-2	3268.72	72.9	74.5	15.3	4.7	1.2	3.5	0.8	1.1	21.7	-	1.4	-	-	2.9	
TN-K-18-7	3270.30	76.6	75.4	14.9	4.5	1.1	3.0	1.1	2.9	19.4	-	0.3	0.9	-	-	
TN-K-18-8-1	3282.74	74.3	67.6	22.4	4.3	1.5	3.9	0.4	2.3	3.1	0.3	4.6	1.7	-	13.7	
TN-K-18-8	3283.60	71.4	69.6	18.8	6.0	0.8	4.4	0.4	2.6	24.0	-	0.6	0.6	-	0.9	
TN-K-18-9	3284.85	74.3	83.5	11.5	1.2	1.2	1.9	0.8	1.7	22.3	0.9	0.3	0.6	-	-	
TN-K-18-10	3295.20	80.9	92.9	1.4	2.5	1.4	1.8	-	3.1	13.7	0.6	1.7	-	-	-	
TN-K-18-9-2	3299.50	65.2	82.9	9.2	0.9	4.8	2.2	-	3.4	2.6	-	5.1	-	-	23.7	
TN-K-18-10-1	3305.55	69.2	94.2	1.7	1.2	2.3	-	0.6	1.6	1.6	0.8	2.0	1.6	-	23.2	
TN-K-18-11	3307.00	70.3	87.4	6.5	3.7	2.0	0.6	-	2.9	24.3	-	1.1	0.9	-	0.6	
UBN-B-75-3	4481.15	71.4	82.0	12.4	2.4	2.0	0.8	0.4	8.9	6.0	0.3	3.1	-	-	10.3	

*denotes contact between carbonate cement (c) and porous area (p)

**denotes same as above, bulk rock point counted

***qualitative point count

* (C) Catalina Number

Table 3.4: Mineralogical Composition of Nibernia Sandstones

Sample	Depth (m)	Det (%)	Recal to 100%							Auth.				
			Qm	Op	Ch	Fsp	Srf	Mrf	Sl	Co	Py	Cy	Ca	Por.
SN-C-13-1	4392.52	92.2	93.8	3.5	0.5	0.5	1.1	0.5	6.5	-	0.5	0.8	-	-
SN-C-13-5-1	4395.30	81.1	63.5	10.2	1.8	1.8	0.4	-	11.1	-	0.9	2.6	-	4.3
SN-C-13-5-2	4396.46	85.7	93.3	3.3	1.0	1.7	0.7	-	11.4	-	0.3	1.1	-	1.4
SN-C-13-2	4400.50	89.1	96.8	1.3	1.0	1.0	-	-	2.6	1.7	1.7	2.3	1.1	1.4
SN-C-13-6-1	4582.90	69.1	90.9	4.1	2.1	2.1	0.4	5.0	3.1	23.1	2.9	0.3	1.4	-
SN-C-13-6-2	4585.33	73.7	84.5	10.1	1.9	1.9	1.6	-	6.6	15.1	0.9	2.6	-	1.1
SN-C-13-3	4586.84	84.0	87.4	7.5	2.7	0.7	1.0	0.7	8.9	3.1	0.9	2.0	1.1	-
SN-C-13-4	4588.29	77.1	90.8	4.8	3.0	0.4	0.7	0.4	0.6	12.0	0.9	1.4	0.9	-
UN-M-22-1	3378.80	83.4	86.3	4.1	2.1	2.8	4.1	0.7	2.6	10.3	0.9	2.3	0.6	-
UN-M-22-2	3392.50	80.6	86.2	5.0	1.4	2.1	4.6	0.7	3.4	14.9	0.6	0.6	-	-
UN-M-22-3	3565.40	85.1	87.9	5.4	2.0	2.0	2.7	-	8.0	3.1	-	2.0	0.9	-
UN-M-22-2-1	3566.27	67.1	78.3	14.5	2.1	2.1	2.1	-	3.7	10.9	1.4	2.9	0.6	-
UN-M-22-4	3566.80	71.7	82.9	10.0	2.0	3.2	1.6	0.4	3.4	24.0	0.6	0.3	-	-
UN-M-22-2-2	3568.87	63.4	88.7	7.2	2.3	0.9	0.9	-	6.3	5.1	0.6	4.0	-	20.6
UN-M-22-5 *c	3569.22	76.6	77.4	14.2	1.5	5.4	1.5	-	5.7	18.3	-	0.9	-	0.6
UN-M-22-5 *p	3569.22	68.0	79.4	16.0	4.6	3.8	0.4	-	9.7	6.6	0.3	4.0	-	11.4
UN-M-22-3-1	3570.20	77.4	88.2	8.1	2.6	1.1	-	-	11.7	1.9	1.7	1.4	-	2.3
UN-M-22-3-2	3572.70	78.3	83.6	4.4	1.8	1.8	1.8	0.4	1.1	19.1	0.9	0.6	-	-
UN-M-22-6	3573.00	78.0	90.5	4.8	1.8	1.5	1.5	-	5.7	11.7	-	2.0	-	2.6
UN-J-49-1 *c	3916.10	73.1	88.7	6.6	1.6	2.3	0.8	-	6.9	17.1	2.0	0.9	-	-
UN-J-49-1 *p	3916.10	64.7	90.7	6.2	0.5	2.6	-	-	5.0	2.3	1.0	3.0	1.3	22.7
UN-J-49-2	3920.50	76.9	93.2	3.6	1.1	1.4	0.7	-	14.3	0.6	0.6	1.7	-	3.7

*denotes contact between carbonate cemented area and porous sandstone

Table 3.5: Detailed Mineralogy of Jeanne d'Arc Sandstones

Sample	Depth (m)	Polycrystalline Qtz			Chert Varieties					Sedimentary Rock Frag			
		Total	plut (<10)	met (>10)	Total	lt gry	dk gry	grn	brwn	Total	duct	slt/est	carb
TN-H-99-1-1	3227.70	10.4	68.4	31.6	3.0	75.3	22.1	2.6	-	1.3	5.6	94.4	-
TN-H-99-1-2 *c	3228.59	11.7	77.9	22.1	1.2	84.2	15.8	-	-	3.1	-	95.7	4.3
TN-H-99-1-2 *p	3228.59	13.9	72.4	27.6	2.9	68.3	31.7	-	-	3.4	-	100.0	-
TN-H-99-1-3 **	3229.95	12.7	77.4	22.6	5.0	86.4	13.6	-	-	3.2	6.3	90.5	3.2
TN-H-99-1-4	3233.78	12.0	75.2	24.8	3.9	92.1	7.9	-	-	1.3	4.6	95.4	-
TN-H-99-2-5	3240.07	12.6	84.4	15.6	2.9	83.1	12.6	4.3	-	2.1	6.9	93.1	-
TN-H-99-2-7 **	3243.45	13.1	74.2	25.8	2.9	89.3	10.7	-	-	4.9	5.4	89.8	4.9
TN-H-99-2-8	3247.25	10.0	85.7	14.3	5.8	94.4	5.6	-	-	6.6	8.2	91.8	-
TN-H-99-3-10	3260.68	15.7	65.3	34.7	2.8	71.9	15.6	-	12.5	3.1	1.3	94.2	4.6
TN-H-99-3-11 **	3261.15	20.7	78.5	21.5	3.3	80.4	8.3	-	11.4	4.4	4.7	92.1	3.2
TN-H-99-3-12	3263.42	14.4	79.6	20.4	2.9	93.5	6.5	-	-	2.2	-	97.9	2.2
TN-H-99-4-13	3268.87	12.4	73.6	26.4	4.1	87.6	12.4	-	-	2.8	-	93.8	6.2
TN-I-97-2-1	3302.08	10.3	70.2	29.8	3.3	88.3	11.7	-	-	2.5	8.7	90.1	1.2
TN-I-97-3	3304.00	11.2	82.7	17.3	1.9	77.6	22.4	-	-	2.8	-	97.8	2.2
TN-I-97-2-2	3305.00	11.1	84.3	15.7	1.5	87.3	12.7	-	-	3.1	-	100.0	-
TN-I-97-3-1	3312.03	16.4	81.2	18.8	4.1	72.0	13.3	-	14.7	3.2	3.3	95.5	1.2
TN-I-97-6	3312.70	10.4	77.6	22.4	4.2	82.7	17.3	-	-	2.1	-	91.6	8.4
TN-I-97-4-1	3314.95	16.8	74.3	25.7	4.4	85.4	4.4	-	10.3	2.0	-	90.8	9.3
TN-I-97-8	3315.60	19.2	95.1	4.9	3.3	79.0	11.7	-	9.4	2.1	-	96.8	3.2
TN-I-97-4-2	3317.86	13.8	76.3	23.7	5.7	91.3	6.4	2.3	-	3.1	-	100.0	-
TN-I-97-5-1 *p	3314.80	11.2	72.2	27.8	3.9	94.7	5.3	-	-	0.8	4.6	92.9	2.6
TN-I-97-10	3323.20	17.5	66.2	33.8	3.0	73.7	22.7	-	3.7	4.1	-	98.8	1.3
TN-I-97-11	3324.30	15.9	90.2	9.8	2.0	80.9	12.6	-	6.6	3.6	-	98.8	1.3
TN-I-97-5-2	3324.55	11.9	83.3	16.7	3.7	85.8	14.2	-	-	3.0	-	100.0	-
TN-I-97-6-1 **	3326.00	13.4	72.6	27.4	1.6	90.8	9.3	-	-	1.6	-	95.4	4.6
TN-I-97-12	3326.00	11.6	81.2	18.8	2.7	90.3	8.5	1.3	-	0.9	-	96.4	3.7
TN-I-97-13	3326.50	12.8	77.4	22.6	2.0	91.6	8.4	-	-	2.5	-	95.4	4.6
TN-I-97-7-2	3327.47	20.0	69.3	30.8	2.5	95.7	4.3	-	-	4.2	-	100.0	-
TN-K-07-3	3329.40	16.9	70.6	29.4	3.9	82.2	12.4	-	5.5	3.9	6.2	90.5	3.3
TN-K-07-5	3338.10	11.1	77.2	22.8	6.0	83.8	9.4	-	6.8	0.5	-	96.4	3.6
TN-K-07-6	3339.80	13.9	74.1	25.9	4.5	89.4	4.3	-	6.4	2.1	-	95.8	4.3
TN-K-07-9	3358.50	13.2	89.3	10.7	0.9	96.3	3.7	-	-	1.4	12.6	87.4	-
TN-K-07-10	3365.01	17.0	79.4	20.6	5.5	79.3	20.7	-	7.3	5.1	-	95.7	4.3
TN-K-07-11	3366.30	13.2	68.3	31.8	1.9	84.3	15.7	-	-	0.8	-	96.8	3.3
TN-K-18-2-1	3218.37	15.5	78.3	21.7	3.1	84.2	7.4	-	8.3	2.3	-	94.4	5.6
TN-K-18-4-1	3248.96	16.4	84.1	15.9	0.5	87.9	5.2	6.9	-	2.3	6.4	93.6	-
TN-K-18-4-2	3254.60	11.5	75.4	24.6	3.3	93.6	6.4	-	-	2.6	-	96.7	3.3
TN-K-18-5	3264.30	13.4	69.3	30.8	1.8	90.9	4.4	-	4.7	2.5	-	100.0	-
TN-K-18-6	3265.60	24.3	83.2	16.8	5.9	83.5	10.3	-	6.2	4.0	-	98.7	1.3
TN-K-18-7-2	3268.72	15.3	77.9	22.1	4.7	92.3	2.3	-	5.5	3.5	-	95.4	4.6
TN-K-18-7	3270.30	14.9	66.3	33.7	4.5	92.5	4.3	-	3.3	3.0	-	96.7	3.3
TN-K-18-8-1	3282.74	22.4	85.4	14.6	4.3	97.6	2.4	-	-	3.9	-	100.0	-
TN-K-18-8	3283.60	18.8	75.1	24.4	6.0	87.0	10.5	-	2.5	4.4	-	97.8	2.2
TN-K-18-9	3284.85	11.5	67.4	32.6	1.2	96.8	3.3	-	-	1.9	-	98.8	1.3

plut: plutonic or undetermined origin

met.: metamorphic origin

l. gry: light grey

d. gry: dark grey

grn: green

brwn: brown

duct: ductile

slt/est: siltstone/sandstone

carb: carbonate (micritic)

Figure 3.1 Sandstone classification scheme (after Folk, 1974) based on ternary plot of quartz, feldspar and rock fragments for Jeanne d'Arc and Hibernia Formations. Only the top part (75% quartz) of the classification scheme is used to demonstrate that most sandstones show little compositional variability in their detrital constituents, plotting as sublitharenites. Coloured symbols represent the average lithological composition for Hibernia sandstones for the well studied. There is an error of approximately 1-2% associated with the percent composition of the components.

Sandstone Classification

sandstones have ratios of almost 3:1 lithic fragments to feldspars. In contrast, Hibernia sandstones contain approximately 2:1 rock fragments to feldspars. The average sandstone composition for Jeanne d'Arc sandstones is $Q_{42} F_2 R_{40}$ and for Hibernia sandstones is $Q_{44} F_2 R_{44}$.

The detrital component of Jeanne d'Arc sandstones ranges from 58.0% to 82.9%, averaging 72.2% of the total rock. In comparison, samples from wells outside of the main Hibernia field penetrating the Hibernia Formation are characterized by a more abundant detrital component, ranging from 63.4% to 92.2% and averaging 77.0% of the bulk rock.

3.2.1.1 Quartz

Quartz is the dominant framework grain and is ubiquitous in the Jeanne d'Arc and Hibernia Formations, ranging from 84.2% to 98.3% and 73.8% to 97.3% of the detrital constituents, respectively. Both monocrystalline and polycrystalline quartz are present. Monocrystalline quartz is the more common of the two, varying from 64.0% to 92.9% with an average abundance of 80.8% compared to poly-crystalline quartz which ranges from 1.4% to 24.3% and averages 11.4% in the Jeanne d'Arc Formation. Hibernia sandstones contain monocrystalline quartz ranging in abundance from 63.5% to 96.8% and averaging 86.5% while composite quartz grains range from 1.3% to 16.0% and average 7.0%.

Undulose extinction (Plate 8) is common in polycrystalline grains whereas most single-grained quartz particles display straight or slightly wavy extinction. Boehm lamellae are rarely observed and are attributed to intense strain that results in the formation of warped, subparallel strain shadows.

Few (approximately less than 5%) of monocrystalline quartz grains

contain inclusions. The most common are vacuoles which impart a brown colour to the quartz grains and occur as trains along grain perimeters (Plate 1) or occur as "negative crystals" resembling the external shape of the quartz grain. Mineral inclusions are also uncommon and include rutile (needle-like), epidote (euhedral) and muscovite (bladed) microlites.

There is a direct relationship between the mean apparent grain size as measured in thin section and the abundance of composite quartz grains (Figure 3.2). Coarser sandstones contain a greater number and variety of polycrystalline quartz than finer sandstones. Two types of composite quartz grains are recognized in thin section based on the criteria of Folk (1974): plutonic and metamorphic (sheared and stretched). An attempt was made to assign individual composite grains to a provenance class in Jeanne d'Arc sandstones (Table 3.5), based on the presence of undulatory extinction, number of sub-crystals and the shape of the boundaries between them. The subdivisions should be treated as an effort to quantify petrographic observations and not as unequivocal quantitative estimations.

Plutonic quartz is the most common type in Jeanne d'Arc sandstones, ranging from 65.3% to 95.1% and averaging 77% of the polycrystalline quartz. This quartz type is characterized by less than 10 sub-crystals, subequant shapes, straight intercrystalline boundaries, straight to slightly undulatory extinction, lack of mineral inclusions and some vacuoles (Plate 8).

Stretched and sheared metamorphic quartz is also common, ranging from 4.9% to 34.7%, and averaging 23% of polycrystalline quartz in the Jeanne d'Arc Formation. These metamorphic quartz grains consist of more than 10

Figure 3.2: Mean Grain Size and Quartz

Figure 3.2 The relationship between apparent mean grain size (as measured in thin section) and the abundance of polycrystalline quartz indicates that coarser sandstones contain more composite grains than finer grained sandstones.

sub-crystals and are characterized by elongate crystals, moderately to strongly undulatory extinction, crenulated or sutured boundaries and presence of mineral inclusions (Plate 9).

3.2.1.2 Chert

Microcrystalline quartz in the form of chert is common throughout the Jeanne d'Arc and Hibernia sequences, ranging from 0.5% to 5.8% and 0.5% to 4.6%, respectively. Chert is more common in coarser samples and in the Jeanne d'Arc Formation (averaging 2.9%) than in Hibernia samples (averaging 1.9%). Well rounded pebble and granule size cherts are especially common in conglomerates of the Jeanne d'Arc Formation. Many cherts are better rounded than quartz grains occurring in the same thin section, suggesting that they have been reworked.

Chert may occur in a variety of colours depending on the impurities (clay minerals, pyrite, carbonate, silt, organic matter) present. As shown in Table 3.3, the most common colour is light grey, accounting for approximately 86.3% of the total chert in the Jeanne d'Arc Formation. Green chert, with coloration attributed to the presence of chlorite, is locally abundant in finer grained sandstones and randomly distributed throughout medium grained sandstones. In coarse sandstones and conglomerates, chert grains appear light brown in colour due to the presence of carbonates.

3.2.1.3 Feldspars

Approximately 46 of the thin sections studied were stained with cobaltinitrate to aid in feldspar identification. Feldspar ranges from

trace amounts to 4.1% in the Hibernia Formation and from 0.3% to 5.0% in the Jeanne d'Arc Formation. Two compositional groups occur (Table 3.3): potassic feldspars (microcline and orthoclase) which stains yellow and plagioclase (Plate 10) which stains pink. Plagioclase dominates in percent over potassic feldspars in both Hibernia and Jeanne d'Arc Formations.

The small proportion of feldspars in thin section may in part be attributed to their lower physical and chemical stability compared to quartz. The decrease from original feldspar content is due to decomposition, chemical alteration (kaolinization, sericitization, solution and vacuolization) and abrasion. Pre-diagenetic feldspar content is a useful measure of the maturity of a sandstone. Feldspars are smaller and better rounded than associated quartz, providing additional evidence that the sandstones are mature. Feldspars are inclusion-poor and lack secondary overgrowths. Rare bent twinning in some plagioclase suggests deformation of crystals.

Alteration products of feldspars may be disseminated throughout the grains or concentrated along cleavages. The latter pattern is more common and results in alteration patterns that are more extensive and more regularly oriented than in quartz grains (Plate 8). Kaolinite flakes are commonly distributed randomly throughout feldspar grains, unlike sericite which is crystallographically controlled.

Dissolution is the most noticeable type of alteration in both Jeanne d'Arc and Hibernia sandstones. Feldspars underwent diagenetic leaching as carbonate cements which may partially or completely replaced them were removed during diagenesis. Dissolution has commonly occurred along preferred crystallographic directions, producing "honey-comb" textures

(Plate 10).

Another common type of alteration product is vacuoles which result in a cloudy brownish appearance of the affected feldspars. Clay pseudomorphs after feldspars are less common and are seen in SEM photos and under plane polarized light as opaque grains with subhedral shapes like those of feldspar laths.

3.2.1.4 Rock Fragments

Rock fragments or polymineralic grains (as opposed to chert and polycrystalline quartz) are more common in coarser sandstones than in finer ones (Figure 3.3) because of their tendency to disaggregate with transport distance and the availability of the fragments closer to source area. Lithic fragments constitute a greater percentage in the Jeanne d'Arc sequence (ranging from 0% to 8.5%) than in the Hibernia sequence (ranging from 0% to 6.6%) (Table 3.1 and 3.2).

Rock fragments were divided into three types depending on suspected provenance: sedimentary (ductile, siliceous and carbonate), metamorphic (schists and metaquartzite) and volcanic. Fragments of older sedimentary rocks predominate, averaging 2.5% in the Jeanne d'Arc Formation and 1.3% in the Hibernia Formation whereas metamorphic grains average 0.7% in Jeanne d'Arc sandstones and 0.4% in Hibernia sands. Volcanic rock fragments are rare in both formations (Plate 9).

Deformed rock fragments (Table 3.3) (Plate 9) appear to dominate in sandstones that occur proximal to shale units and include shaly and mud rip-up clasts. Microscopically these soft components consist of finely crystalline clay particles with poorly defined orientation, and are

Figure 3.3: Rock Fragments and Size

Figure 3.3 Polymineralic grains, (rock fragments as opposed to chert or polycrystalline quartz) including sedimentary and metamorphic rock fragments, are more common in coarser sandstones than in finer ones as indicated in a plot of the abundance of rock fragments versus apparent mean grain size.

commonly deformed or embayed by adjacent rigid quartz grains to form irregular, discontinuous, elongate, flattened wisps or pseudomatrix (which is commonly confused with true matrix (Plate 11)). Such compaction is usually accompanied by a significant reduction in primary porosity. In sandstones that underwent early carbonate cementation, compactional deformation of ductile rock fragments has been prevented or minimized.

Siltstone and fine sandstone fragments are uncommon because of their tendency to break down under transport into finer components. Transport distances are therefore assumed to be minimal in samples where these clastics occur. Micritic calcite rock fragments and sparry calcite grains are observed in few Jeanne d'Arc sandstones (Plate 11), but are absent in the samples studied from the Hibernia Formation. These carbonate rock fragments are commonly well rounded, equidimensional or slightly ovoid and may show compaction features.

Metamorphic rock fragments consist principally of aggregates of micas, clays and fine-grained quartz and are distinguished from sedimentary rock fragments (Plate 12) by their rigidity and oriented fabric. The most common metamorphic rock fragment (excluding metaquartzites) are quartzose schists, characterized by strongly serrated and crenulated boundaries between quartz sub-crystals, undulatory extinction and varying amounts of mica and feldspars.

Volcanic rock fragments are rare in both formations and contain feldspar laths in an aphanitic groundmass (Plate 9).

3.2.2 Accessory Minerals

The most common igneous accessory is hornblende, identified by its

pleochroism in plane polarized light and its cleavage. Other accessory minerals (heavy minerals) found in trace quantities include: zircon, garnet, apatite and epidote.

3.2.3 Carbonaceous Material

Carbonaceous material accounts for up to 1.4% of the total rock volume in the samples of the Hibernia Formation and for up to 4.6% in the Jeanne d'Arc Formation. Most carbonaceous debris consists of insoluble organic matter such as deformed and undeformed plant fragments (Plate 12). The colour of the material is a reflection of the thermal maturation and thickness of the detrital particle and ranges from light brown to black. Abundant organic matter occurs locally as "coaly" seams (Plates 13), disseminated blebs and recognizable woody chips, branches or leaves and is commonly associated with pyrite. Bitumen coated quartz is present in one Terra Nova sample from C-09 well.

3.2.4 Fossils

Ichnofossils are present but not abundant in observed Hibernia and Jeanne d'Arc cores. They are usually confined to the top sections of silty shale and shale units, but they also occur in some fine sandstones. Based on comparison with illustrations in Chamberlain (1978), the most common types are the narrow feeding tubes of Chondrites and Skolithos.

Fossil shells (fragmented and whole) are conspicuously absent in sandstones from the Jeanne d'Arc Formation. Fragments of gastropods, ostracods, forams and pelecypods are rarely present in the Hibernia and Catalina samples studied.

3.2.5 Matrix

Sandstones from both Hibernia and Jeanne d'Arc Formations contain little or no interstitial matrix except in a few fine-grained sandstones, siltstones and poorly sorted sandstones (Plate 11) (Tables 3.1 and 3.2). It consists of silt-sized quartz and other silicates (mostly clays) and was qualitatively distinguished from framework grains on the basis of relative size compared to framework grains.

3.3 Authigenic Minerals

Authigenic minerals, including quartz, carbonates and clays are important constituents in Jeanne d'Arc and Hibernia sandstones, constituting 6.0% to 34.3% and 7.8% to 29.4%, respectively of the total rock volume.

3.3.1 Quartz Overgrowths

Quartz overgrowths are ubiquitous in both formations, ranging from 1.1% to 14.3% in Hibernia sandstones and from trace to 8.9% in Jeanne d'Arc sandstones. Overgrowths are distinguished in thin section by authigenic grain-coating clays or dust rims, separating them from original grain boundaries and by euhedral grain boundaries. SEM and petrographic studies show that well developed quartz overgrowths are particularly common in sandstones showing no evidence of early carbonate cementation (Plate 8). Under cathodoluminescence, quartz overgrowths are indistinguishable from their detrital host; however, some thin rims (clay coatings) separating the detrital core from the silica cement are slightly luminescent. This may be attributed to trace element (Mn for example)

impurities in the clay minerals.

3.3.2 Carbonate Cements

The most abundant authigenic phase in Jeanne d'Arc sandstones are calcite and dolomite cements, averaging 12.9% of the sample volume (Plate 13). In thin sections stained with alizarin red-S and potassium ferricyanide, both ferroan calcite and ferroan dolomite cements appear blue.

Calcite and dolomite pore-filling cements rarely co-exist together in the same sample in Jeanne d'Arc sandstones. Calcite occurs as late fracture-filling coarse-grained spar, as early pore-fillings of primary porosity, as part of a poikilitopic network, and as remnant patches postdating decarbonatization. Highly cemented sandstones contain 15% to almost 28% calcite or dolomite cements and are characterized by an uncompacted appearance with floating grains (Plate 13), which is attributed to partial or complete replacement of framework grains (feldspars and rock fragments) (Plate 11) and of quartz overgrowths. Porous sandstones may contain remnant patches of cements, a relict of original pore-filling cement which preceded dissolution of carbonate cements. These remnants, separated by secondary pores, are sometimes in crystallographic continuity, suggesting that they were once part of the same poikilitopic network.

Non-ferroan dolomite is common in the Jeanne d'Arc Formation but is not observed in samples studied from the Hibernia Formation. This cement (as seen under cathodoluminescence and corroborated by S.E.M and XRD) may be homogeneous or show compositional zoning. Iron concentration gradients

The remnant patches of dolomite rhombs commonly exhibit iron depletion in a traverse from rim to core (Plate 14). Ferroan (ankeritic) dolomite is also common.

Siderite is a minor authigenic constituent. It is microgranular, sucrosic and brownish in appearance. Rare microspherulitic siderite also occurs. Flattened siderite rhombs are commonly present in sandstones that overly or underly shales that contain siderite nodules (Plates 14 and 15).

3.3.3 Clay Minerals

All major types of clays are known to form authigenically in sandstones either as a direct precipitate from formation waters or through reactions between precursor minerals and the contained waters. Identification of these phyllosilicates is based on morphological and textural characteristics distinguished by petrographic study, SEM, EDX, and XRD analysis.

Clay minerals occur in close association with some feldspars as partial or complete replacements (pseudomorphs) and elsewhere fill or line pore spaces. The relative abundance of different clay minerals was semi-quantitatively estimated by measuring the peak area of the first order reflection (7.2 Å for kaolinite, 10 Å for illite and 14 Å for chlorite) on x-ray diffractograms and qualitatively estimated using S.E.M. photographs.

Kaolinite is the most abundant clay followed by illite, chlorite and sericite (Plates 16 and 17).

Kaolinite crystals (pseudo-hexagonal platelets stacked face to face) are visible on altered feldspar grains and in pore spaces usually adjacent to feldspars. Illite is recognized in thin section by its "cornflake"

appearance and by the presence of a potassium peak in the x-ray spectra.

Chlorite is rare, occurring as fibrous, greenish thin grain coats around feldspar grains and rock fragments in the Jeanne d'Arc Formation. The occurrence of this mineral in thin section is corroborated by SEM studies (Plate 16) and XRD analysis. It was not observed in the samples selected from the Hibernia Formation. Sericite occurs as irregular platelets in trace amounts and is associated with the alteration of feldspar minerals in the Jeanne d'Arc Formation.

The source of the metallic cations for diagenetic clay minerals are subjacent mudrocks or dirty sands.

Clay coatings which remain intact around partially or completely dissolved framework grains are the strongest evidence for diagenetic dissolution of framework grains.

3.3.4 Pyrite

Pyrite ranges from 0% to 2.9% in the Hibernia Formation and from 0% to 8.6% in the Jeanne d'Arc Formation. It occurs as irregular patches, clusters of euhedral cubic crystals, (Plates 17 and 18) and incipient cement lining, commonly replacing carbonaceous material. In core samples elongate pyrite aggregates occur parallel, perpendicular and at slightly oblique angles to bedding surfaces indicating precipitation from Fe-rich solutions controlled by various factors including permeability. Early pyrite forms at or near the surface of sedimentation under reducing conditions and is associated with decaying organic matter.

3.4 Porosity

Porosity values range from trace amounts to 22.7% and 24.9% in Hibernia and Jeanne d'Arc sandstones, respectively. Both primary and secondary porosity occur with the latter the more abundant of the two. Criteria for distinguishing secondary porosity from primary includes: corroded grains, honey-comb grains, adjacent porous and less-porous zones, remnant cement, inhomogeneity of packing and sinuous pores. Porosity will be discussed in detail in Chapter 6.

3.5 Diagenetic Sequence

The proposed diagenetic sequence for the Jeanne d'Arc Formation (Figure 3.4) is strongly influenced by the study in cores of interfaces between tightly cemented sandstones and adjacent more porous regions which are interpreted as either dissolution fronts representing decarbonatization episodes or as precipitation fronts resulting from dissolution and reprecipitation processes during rock-fluid interactions. These contacts are characterized by irregular, diffuse and abrupt boundaries and may serve as either a transition zone or a chemical barrier between contiguous regions depending on their origin. Diffuse boundaries are interpreted as representing dissolution processes, based on textural similarities across the contact. More abrupt boundaries are interpreted as precipitation fronts involving prior dissolution (elsewhere in the sandstone), followed by removal and transport of minerals in solution with subsequent reprecipitation at the contact. The precipitation contacts are the result of localized early calcite cementation.

Early burial is characterized by mechanical compaction which is most

Figure 3.4: Schematic representation of the diagenetic sequence for Jeanne d'Arc sandstones. The width of the diagenetic bar corresponds to the prevalence of the diagenetic phase during burial. The discontinuous segments represent phases which were not widespread during that interval.

evident in Jeanne d'Arc sandstones that did not undergo early silica or carbonate cementation. A large part of the original porosity has been lost due to compaction as suggested by ductile grain deformation and the development of long and concavo-convex grain contacts. However, many framework grains appear to be floating or have point contacts which suggests early cements filled original porosity to stabilize the detrital framework and minimize compaction.

Early burial is also characterized by the incomplete precipitation of quartz cement (overgrowths) and minor pyrite in voids. Silica precipitation occurred after authigenic clay rimming of detrital quartz grains but preceded calcite precipitation. In some samples, there are relatively few contacts between quartz cements, suggesting that silica was precipitated after the detrital quartz particles had adjusted to initial overburden pressure. However the presence of long and interpenetrating quartz overgrowth contacts (Plate 8) suggests that silica cementation occurred before chemical compaction.

Silica cement may be precipitated at shallow depths by surface waters containing sufficient silica. Additional sources of silica in Jeanne d'Arc sandstones include:

- 1) silica dissolved in circulating fluids by flow over quartz grains in sandstones;
- 2) liberation of silica during mineral reactions such as the alteration of plagioclase feldspars (Kaolinization) and mafics to clays;
- 3) the conversion of clays (smectite to illite) and
- 4) pressure solution which involves quartz dissolution at points of grain contacts as a result of the increase of quartz solubility at these

points due to overburden pressure (Leder, 1986; Blatt, 1979).

In samples where both carbonate and quartz cements occur, carbonate postdates quartz overgrowths as suggested by partial grain replacement by carbonate (along grain margins) (Plate 13). The precipitation of quartz overgrowths was followed by calcite and dolomite cementation as pore-fillings or complete or partial replacements of feldspars and rock fragments. Where early calcite cementation did not occur, silica cementation and compaction were responsible for reducing primary porosity significantly.

Porosity enhancement resulted from the dissolution of carbonate cements. This dissolution led to the formation of secondary porosity and is largely responsible for the reservoir quality of the Jeanne d'Arc Formation. Secondary porosity is most noticeable in those sandstones that were completely cemented by early calcite before compaction. Most of the original porosity was recovered by the subsequent dissolution of these cements.

Post-dissolution ferroan carbonate cements are recognized in the Jeanne d'Arc Formation.

A second generation of quartz overgrowths is suggested by the rare presence of euhedral crystal outlines in porous sandstones, the close spatial association of corroded quartz overgrowths and non-affected overgrowths and by the extension of these second generation overgrowths into secondary pores.

Late brittle fracturing of quartz grains, although not pervasive evidently occurred after dissolution and development of secondary porosity as implied by the presence of unhealed fractures. This late

compaction phase was followed by late clay (mainly kaolinite), late carbonate and pyrite precipitation, partially infilling secondary pores.

Chapter 4: Secondary Porosity Evolution

4.1 Introduction

Compaction, precipitation and dissolution are responsible for modifying reservoir properties during burial and contribute to the variability of Jeanne d'Arc sandstone porosity. Porosity reducing processes include cementation, replacement, recrystallization and mechanical compaction. The principal form of effective porosity in the sandstones is secondary, resulting from dissolution of framework grains and/or carbonate cement. The timing of porosity enhancing processes is critical with respect to the accumulation and trapping of hydrocarbons.

Schmidt and MacDonald (1979) (using terminology of Choquette and Pray (1970) for carbonate diagenesis) divided sandstone diagenesis into three regimes: eodiagenesis occurring at or near the surface of sedimentation (before compaction), mesodiagenesis occurring during effective burial where strata is sealed from the influence of surface agents and telodiagenesis occurring at or near the surface after effective burial (after compaction). They proposed four textural stages of sandstone diagenesis during effective burial (mesodiagenesis). In order of progressive burial these include:

1. immature stage in which primary porosity is reduced by mechanical compaction,
2. semi-mature stage defined by the onset of pervasive chemical compaction and dissolution with dissolved material reprecipitating as pore cement,
3. i/ mature stage a: characterized by the absence of primary porosity and the development of significant secondary

porosity,

ii/ mature stage b: which involves the gradual destruction of this porosity by chemical compaction with little or no generation of new pore space and

4. supermature stage in which all porosity is at irreducible levels.

4.2 Primary Porosity

Sands are deposited with original porosity (intergranular) of at least 40% (or higher if they are mature) depending on depositional environment (Pryor, 1974; Beard and Weyl, 1973; Larsen and Chilingar, 1967; Selley, 1980; Hayes, 1979) and packing arrangements. Jeanne d'Arc sands were likely deposited with relatively high porosities as suggested by high pre-cement porosities (present porosity + intergranular cement), low proportion of matrix matter and mechanically unstable lithic fragments.

Although the pores within Jeanne d'Arc sandstones are a combination of primary and secondary, presently the volume of secondary pore space exceeds that of remnant primary pores, based on textural criteria proposed by Schmidt and MacDonald (1979). This is a consequence of diagenetic cementation and leaching of unstable minerals in the shallow subsurface which altered the mineralogy of the original deposits and their response to burial.

Two types of primary porosity are observed: intergranular and intragranular. Primary intergranular porosity, although composing only a small fraction of the total rock volume, is ubiquitous in Jeanne d'Arc

samples and is recognized by its regular distribution and morphology as compared to secondary pores. Intraparticle pores, however, are rare (<< 1%) and occur in fossil-bearing Hibernia samples and in Jeanne d'Arc samples with abundant chert with microporosity.

4.3 Porosity Reduction

The history of porosity reduction with depth in the Jeanne d'Arc Formation is related to compaction and early quartz overgrowth, carbonate, clay and pyrite precipitation.

4.3.1 Compaction

Compaction due to overburden pressure begins soon after initial burial and reduces original porosity by plastic deformation of ductile sand grains, rotation of grains and by fracture or cleavage of brittle grains (Schmidt and MacDonald, 1979). Resulting sutured, concavo-convex or long grain contacts (Plate 8) may represent mechanical accommodation of the bulk rock as the framework collapses with loss of supporting structure.

Less competent grains, mainly sedimentary rock fragments such as shale and mud clasts, may be squeezed between neighbouring rigid (quartz) grains, resulting in destruction of intergranular pores and creation of diagenetic fine-grained pseudomatrix. Total matrix, including pseudomatrix is varies from trace amounts to 4.6% of the total rock volume.

Sublitharenites with considerable mechanically and chemically unstable grains, like those of the Jeanne d'Arc Formation, will be compacted more and faster than those composed mainly of quartz grains, the

quartz arenites. If compaction proceeds rapidly during burial, porosity and permeability are reduced, retarding circulation of fluids from which intergranular cements could have been precipitated. This may be suggested for those Jeanne d'Arc sandstones (Table 3.3) composed of a relatively high proportion of unstable detrital grains which appear to have corresponding low proportions of cement.

Pre-cement porosity is a measure of the porosity present after early compaction (mesodiagenetic immature stage) but before cementation (semi-mature stage) and may be an indication of the maximum depth before which cementation occurs (Damanti and Jordan, 1989). Histograms of frequency distributions of pre-cement porosity and present total porosities for Jeanne d'Arc sandstones, to determine the contribution of compaction (and cementation) during early diagenesis, are shown in Figure 4.1.

The mean pre-cement porosity of Jeanne d'Arc sandstones is 28% (Figure 4.1 a). If it is assumed that the sands were deposited with an original porosity of approximately 40%, then approximately 12% ($40\% - 28\%$) of the original porosity was lost due to mechanical compaction prior to cementation. Because the mean present porosity is 12% (Figure 4.1 b), then 16% ($28\% - 12\%$) of the porosity was lost due to cementation. Therefore, porosity reduction by compaction is only a proportion (42%) of the total porosity reduction because early cementation stabilized the detrital framework.

Calculated mean present and pre-cement porosities instead of frequency distributions were used for Hibernia sandstones because many of the samples showed little visible present porosity as a result of

Figure 4.1 a) The average pre-cement porosity for Jeanne d'Arc sandstones is measured by the frequency distribution. Pre-cement porosity was calculated using the sum of the total present porosity observed and the total non-replacive intergranular cements present.

Figure 4.1 b) The average total present porosity observed for Jeanne d'Arc sandstones is represented on the frequency distribution plot. In many sandstones (represented by the height of the peak at 0%), extensive cementation has occluded all post compactional and primary porosity.

extensive carbonate cementation. The mean present porosity is almost 7% and the pre-cement porosity is about 24%; therefore the porosity lost due to compaction is approximately 16% while the porosity lost due to cementation is 17%. This suggests that Hibernia sandstones underwent slightly more compaction (statistically insignificant) (Plate 19) than Jeanne d'Arc sandstones before the onset of cementation, although the porosity lost due to cementation was relatively the same in both formations.

Abid 's (1988) study showed that the average porosity loss due to compaction (16-17%) is more important than the porosity loss due to cementation in the (13%) Hibernia Formation. Mechanical compaction in Hibernia sandstones is advanced, especially in horizons that escaped early cementation (Abid, 1988). The resulting porosity loss due to compaction is slightly higher in the younger Hibernia sandstones.

Mechanical compaction involves the loss of pore water by compression resulting from the deposition of overlying sediment (Berner, 1980). It causes the centres of grains to be brought closer together with time (Friedman and Saunders, 1978) and the accompanying fluid expulsion and reduction of both volume and porosity is limited by the resistance of grains to deformation and repacking (Larsen and Chilingar, 1976). Therefore packing parameters (density and proximity) may be used to monitor textural relationships during compaction.

Packing proximity and density values show a wide variation with depth because of several inter-dependent factors such as sorting, grain size and grain shape. Figure 4.2 shows packing proximity (ratio of grain contacts to total contacts) versus depth relationships of Jeanne d'Arc

Figure 4.2: Packing Proximity and Depth

Figure 4.2: Packing arrangements do not vary systematically with depth because of early diagenetic processes (cementation and compaction). Sandstones having low packing proximity occur at all depths, while those having higher proximity values appear to plot at shallow depths.

samples. Two trends are distinguishable. Samples having numerous grains in contact with cements and/or porosity have low packing proximity and do not appear to be depth-related. Low proximity suggests either the detrital framework was supported by early precipitation of authigenic minerals and mechanical compaction was minor or that there was significant development of secondary porosity by decarbonatization and framework grain dissolution (mature stage a), resulting in diagenetic textures characterized by irregular, elongate and oversized pores. A larger number of grain contacts, indicated by higher packing proximity, is generally restricted to shallower depths and suggests that early compaction (immature stage) occurred before the onset of carbonate, silica and clay cementation. On the other hand, early cementation before compaction or other processes occurring at deeper burial such as dissolution may have minimized packing proximity at depth.

Several sandstone compaction curves have been proposed that may reflect not only compaction but also cementation and pressure solution. According to Baldwin and Butler (1985), the most suitable frame of reference for loss of pore space is the proportion of solid grains (solidity) as a percentage of the total volume of sediment. After compaction the total volume of the rock, pore space and percent porosity changes but the grain volume (solidity) remains the same. Most Jeanne d'Arc sandstones plot below the Sclater-Christie (Sclater and Christie, 1980) proposed curve (Figures 4.3), suggesting they either have lower solidities (higher porosities) (undercompacted) than expected for the depths at which they occur or the solidities (porosity) is preserved with deeper depth. On the other hand those points plotting above the

Figure 4.3 a) Compaction Curve

(after Sclater and Christie, 1980)

Figure 4.3 a) Exponential curve for texturally and mineralogically mature sandstones (after Sclater and Christie, 1980). When solved for burial depth it takes the logarithmic form:

burial depth (in km) = $3.7 \ln (0.49/1-S)$, where S is solidity (the proportion of solid grains).

The curve appears to be a straight line when compared to the depth interval of Jeanne d'Arc sandstones (Figure 4.3 b).

Figure 4.3 b) Compaction Curve

(after Sclater and Christie, 1980)

Figure 4.3 c) Jeanne d'Arc Compaction

Figure 4.3 c) Plot of solidity versus depth for Jeanne d'Arc sandstones. Most sandstones plot below the Sclater-Christie compaction curve shown suggesting they have lower solidity (higher porosity) at depth than expected. Under-compaction suggests the sandstones were cemented early. Solidity was calculated based on detrital grain content.

Figure 4.3 d) Jeanne d'Arc Compaction

Figure 4.3 d) Plot of solidity versus depth for Jeanne d'Arc sandstones using detrital grains plus the amount of authigenic cements for solidity. The points strongly deviate from the Sclater-Christie curve, suggesting early cementation inhibited compaction and the sandstones were undercompacted.

compaction curve suggest solidities are higher (lower porosity) than expected and they were overcompacted.

The deviation from the Sclater-Christie curve indicates the sandstones have not undergone equal amounts of compaction and this may be attributed to early cementation and/or later cementation and dissolution.

Cementation may continue after compaction has ceased, with significant precipitation of minerals in pore spaces and partial or complete replacement of detrital minerals. Dissolution may begin soon after the onset of cementation and may continue through later diagenesis resulting in significant secondary porosity development at depth. Those points that are interpreted to be undercompacted were cemented early, thus preserving porosity. On the other hand those points which appear to be overcompacted (porosity is less than expected) underwent compaction before cementation.

Compaction may also occur later in diagenesis recommencing after cementation and dissolution processes have ceased. This late compaction phenomenon is manifested as brittle rather than ductile deformation of framework grains. Late microfracturing of grains in the Jeanne d'Arc Formation is evident in coarser grained sandstones and conglomerates. These fractures are usually confined to individual grains, but some extend outside of single particle boundaries, affecting a number of framework components.

4.3.2 Cementation

Precipitation and dissolution of authigenic minerals are more important than compaction in changing porosity during diagenesis in the Jeanne d'Arc Formation. Cementation also influences permeability by occluding porosity and by narrowing of pore throats in primary

intergranular pores.

There appear to be two trends in the relationship between cementation and pre-cement porosities when the two are compared (Figure 4.4). There is a limiting linear trend where most of the pore volume remaining after compaction is filled with cement, suggesting cementation inhibited compaction and a less distinguishable scatter trend where the porosity remaining after compaction is less than the volume of cement of cement available, suggesting cementation occurred after compaction.

Early silica and carbonate cementation (pre-compaction) is noted in the Jeanne d'Arc Formation by the occurrence of corroded quartz overgrowths, detrital grains floating in carbonate cement and high pre-cement porosities. Silica and clay authigenesis had a minor effect on reservoir porosity, as suggested by the small volume of pore space occupied by each.

Early carbonate cementation and grain replacements in some sandstones occluded much of the primary intergranular porosity, most likely during the last two-thirds of the semi-mature stage of mesodiagenesis (Schmidt and MacDonald, 1979), although carbonatization can occur at any stage of diagenesis. Because of carbonate solubility, destruction of porosity by carbonate precipitation is not permanent. Large volumes of detrital grains are replaced by carbonate and silica is held in solution and is available for re-precipitation later.

Carbonate distribution does not vary systematically with depth but is strongly related to secondary porosity development. There is a weak inversely covarying relationship between present porosity and the amount of carbonate cements (Figure 4.5), suggesting the greater the porosity

Figure 4.4: Cementation and Compaction

Figure 4.4: The relationship between cementation and compaction is shown in a plot of cementation and pre-cement porosity. Two trends are evident: a (limiting) linear trend which suggests that most of the porosity after compaction was filled with cement (that is cementation inhibited compaction) and a scattered trend suggesting cementation occurred after compaction.

(mostly secondary) the less carbonate cement occurs in pore spaces, or with less porosity a greater proportion of void space is filled with carbonate cements. Because there is a direct relationship between the loss of porosity due to cementation (pre-cement porosity minus present porosity) and (carbonate cementation) (Figure 4.4), then other processes such as dissolution must also be occurring (together with the precipitation of other minor cements).

4.4 Secondary Porosity

Porosity enhancement results from framework grain dissolution (dissolution of original soluble constituents such as feldspars (Plate 19) and rock fragments) and/or decementation (dissolution of previously deposited cements). The bulk of framework grain dissolution occurs upon moderate to deep burial after significant compaction was completed as evidenced by the presence of insoluble authigenic rims around detrital cores. Carbonate cements are much more soluble than silica cement and are therefore more likely to be dissolved during diagenesis under certain burial conditions. Decementation leaves behind relict textures such as embayments (Plate 9), honeycombed grains (Plates 10 and 19) corroded grain boundaries (Plate 8), moldic pores and remnants of the original pore filling (Plate 20). Decementation processes require a change in the composition of pore fluids from supersaturated to undersaturated with respect to cement mineralogies.

4.4.1 Types of Secondary Porosity

Secondary porosity ranges from trace amounts to 24% of the bulk rock

volume and its preservation depends on grain fabric to support overburden pressure after cement and grain dissolution (Holland, 1984).

For simplicity porosity is divided into three types, excluding fracture porosity (which enhances all porosity types): intergranular, dissolution and micro-porosity. Intergranular porosity resulting from the dissolution of replacive cements are the most common type in the Jeanne d'Arc Formation while dissolution pores resulting from framework grain dissolution do not contribute significantly to secondary porosity development (most likely due to the maturity of the sandstones). Intergranular porosity is commonly solution enhanced (enlarged by solution along grain margins leading to the formation of corroded grain boundaries) while dissolution pores develop at the expense of certain compositional elements, especially lithic fragments and feldspars. Framework grain dissolution occurs upon moderate to deep burial as supported by the presence of authigenic rims (incomplete dissolution of the grain, leaving behind an insoluble rind of an authigenic material or a small amount of insoluble debris) around dissolution pores which are unaffected by compaction processes (Siebert et al, 1984).

Moldic and intragranular porosity also result from dissolution of labile grains such as chert and feldspar replaced by carbonate cements. Chemically unstable minerals may be susceptible to diagenetic processes involving in-situ dissolution (Pitman et al, 1987). However, it is unlikely that intragranular porosity resulted from the direct dissolution of siliceous detrital grains, but these grains were first replaced by cements prior to dissolution. Examples include: honey-combed feldspar and porous chert grains.

Feldspar dissolution is crystallographically controlled with incipient dissolution along cleavage planes (Plate 19) or total dissolution leaving subhedral molds. Leached feldspar is often turbid due to incipient sericite or vacuoles. Kaolinite and relict grains of partially dissolved feldspars are observed in some secondary pores. Chert grains commonly exhibit intragranular rhombic porosity and grain margins that have been indented by rhombic reentrants, suggesting carbonate cement replacement and subsequent dissolution. There are two types of dissolution processes evident in the Jeanne d'Arc Formation: 1) congruent dissolution in which the solid phase dissolves homogeneously, leaving behind fresh surfaces of undissolved solid which is unaltered in composition. Feldspars and rock fragments can dissolve completely, leaving behind grain-sized pore spaces with little evidence of the original grain (Plate 20). 2) incongruent (selective) dissolution in which solid mineral grains dissolve and react with pore fluids such that the solute and residual solid are different in composition from the original solid phase because only some of the components of the original crystal are leached into solution (Pettijohn et al, 1987). An example of this process is the kaolinization of a feldspar which begins early during diagenesis (Plate 20). Kaolinite replaces plagioclase grains and may grow outwards to fill surrounding pore space.

Direct dissolution of silicate minerals creates little or no secondary porosity because dissolution occurs along grain contacts. However silicate minerals replaced by carbonate minerals may be dissolved by removal of the replacive cement.

Microporosity is most evident in sandstones with pore-filling clay

mineral aggregates, as is clearly evident in SEM photographs (Plate 16).

Many of the fractures present in Jeanne d'Arc sandstones have been filled with late calcite cement. There does not appear to be any relationship between fracture width observed in drill cores and depth. Mineralized fractures commonly cut across authigenic minerals, indicating that the development and cementation of fractures occurred late in the burial history. Fractures may have formed in response to high pore pressures that developed during burial and to stress gradients that occurred during regional tectonism (Pitman et al, 1987).

4.4.2 Solution Fronts

Several lenses are visible in core intervals where cement dissolution has not occurred. These areas are in contrast to sections immediately above and below which have no cement and high porosity. The contact between these two areas can be gradational or abrupt.

Where the contacts are gradational remnant patches of carbonate cement occur in the transition and porous zones. Carbonate replacement of grain margins in cemented regions and corroded grain boundaries in porous areas suggest that the secondary porosity observed is due to carbonate leaching, with minor contribution from framework grain dissolution.

The transition from carbonate-cemented sandstone to porous sandstone across a gradational contact within continuous core thus reveals evidence for carbonate dissolution by:

1. corroded remnants of carbonate cements in transition zone
2. corroded grain boundaries in porous zone
3. occurrence of carbonate remnants separated by open pore space

that are in optical continuity,

4. solution of interior and exterior of feldspar replaced by carbonate
5. kaolinite precipitation in oversized pores
6. textural similarities (packing) are apparent in a traverse across the contact.

Abrupt contacts between porous and highly cemented areas may suggest a precipitation front in which carbonate minerals dissolved elsewhere were re-precipitated by geochemical evolving fluids.

4.5 Mechanisms for Secondary Porosity Development

Secondary porosity by dissolution requires a through-flow of pore water within a reservoir unit such that the fluid is undersaturated with respect to one or more of the major mineral phases present (Bjorlykke, 1984; Holland 1984). Removal of large amounts of material in solution without extensive reprecipitation requires maintenance of low solute concentrations (Stonecipher et al, 1984). As temperature and the rate of hydrocarbon generation increases, chemically active aqueous solutions moving from mudstones into sandstones dissolve and flush away certain sandstone components, creating secondary porosity. Flushing of large volumes of water through Jeanne d'Arc sandstones is suggested by unstable minerals such as clay clasts and feldspars which show partial to complete dissolution. Effective porosity may be produced if pore fluids remove soluble framework grains and cements in quantities that allow flow channels to be created. Because early diagenetic carbonate cements (and replacements) are the main constituents that are dissolved from

sandstones, it is likely that acidic solutions produced by CO₂-charged waters in the subsurface as a result of organic, inorganic or a combination of both processes (Franks and Forrester, 1984; Hughes, 1979) were involved.

Shale water is the likely origin of solvents capable of dissolving carbonate cements and framework grains because of its availability and proximity to sandstones and the existence of a pressure gradient to move the fluid from the shale into and out of the sandstone (Siebert et al, 1984). Compacting shales release interlayer water as the result of clay mineral transformations (conversion of smectite to illite) and expel fluids as a result of the maturation of organic material (kerogen to hydrocarbon) such that subsurface reservoirs become undersaturated with respect to carbonates and other minerals and dissolution occurs (Schmidt and MacDonald, 1979).

4.5.1 Shale Compaction

Shale compaction in the subsurface yields large volumes of acidic pore water which may enter more permeable interbedded sandstones through fractures developing in shales as a result of hydrocarbon and CO₂ generation (Holland, 1984). Jeanne d'Arc sandstones are dissected by numerous faults which may have served as conduits for fluid flow. These fluids may flow laterally through the sands, becoming available for dissolution reactions as the shales expel cations which may change and homogenize the composition of water in the pores of sandstones (Cant, 1986). The input of large quantities of fluid provides a renewable source of CO₂ released by organic maturation to allow replacement by

carbonate and precipitation of carbonate in pores. Acid pore waters move through shales that contain carbonate but subsequently leach carbonate from sandstones, possibly because of the neutralizing effect of feldspars in shales.

4.5.2 Organic Maturation

Sediments containing organic debris produce carboxylic acid during diagenesis by thermocatalytic degradation of kerogen in source rocks which may be available for porosity enhancement depending on the following (Surdam et al, 1984):

1. pH of interstitial fluids,
2. mineralogy of framework grains and cements,
3. ratio of inorganic (sand) to organic (shale) matter,
4. composition of the organic material and
5. fluid flux

Decarbonatization corresponds closely with the rate of production of CO_2 in intercalated shales resulting from decarboxylation of maturing organic matter. The amount of CO_2 expelled during kerogen maturation depends on the type of kerogen (Schmidt and MacDonald, 1979; Surdam et al, 1984). Type III organic matter has a higher potential of generating CO_2 than type II (herbaceous) kerogen because of its high oxygen content (Franks and Forrester, 1984). Peak generation of CO_2 from kerogen occurs at approximately 100 degrees Celsius (Franks and Forrester, 1984).

Carboxylic acids, short chain organic acids are intermediate products between long chain humic acids and the generation of hydrocarbons. These fatty acids and other organic compounds release CO_2 as

they are broken down into simpler compounds, i.e. carbonyl, methoxyl and phenolic hydroxyl groups (Blatt, 1979; Franks and Forrester, 1984). Carboxylic acids are water soluble and their mobility depends on water-releasing reactions in source rocks (smectite to illite reactions) and dehydration (opal-CT to quartz transformation) (Surdam et al, 1984). If source rocks and sandstones are hydraulically connected, then porosity enhancement should occur in areas of the reservoir where original porosity was high.

4.5.3 Aluminosilicate Dissolution

Elevated PCO₂ cannot be the cause of dissolution of aluminosilicates and the presence of carbonic acids will have little effect on silicate framework grains (Surdam et al, 1984). The early maturation of organic matter produces acids capable of dissolving aluminosilicates, ligands (organic complexing agents) which hold the dissolved aluminum in solution and methane which provides part of the pressure for fluid migration (Siebert et al, 1984). The solvent solution is expelled into adjacent sandstones where susceptible aluminosilicate grains are dissolved.

Porosity enhancement as a result of feldspar dissolution requires mobility of Al during diagenesis. Smectite to illite clay transformations in shales reduces the total Al concentration in shale water so that additional Al can be dissolved and complexed when shale water enters the sandstone (Siebert et al, 1984). Organic complexing agents are generated in shales by the maturation of kerogen which produces short chain aliphatic acids (Siebert et al, 1984). These organic complexing agents increase the solubility of aluminum from alumina-silicate minerals.

Organic complexing of Al initially prevents supersaturation with respect to kaolinite and depends on pH and the activity of Ca^{2+}

Al migrates as an organic complex, and transport reduces the acidity in the zone of ligand production and increases in zone of ligand destruction (Surdam et al, 1984). Aluminum and silica released into solution must be inhibited from precipitating in sandstone pores as clays or other authigenic minerals. Dissolved aluminum must be complexed so that it can be removed from sandstone using volumes of water available in the sandstone/shale sequence, and the solvent solution must be capable of dissolving some aluminosilicates but not dissolving coexisting calcite.

Chapter 5: Carbonate Cement Geochemistry of the Jeanne d'Arc and Hibernia Formations

5.1 Introduction

Diagenesis spans a spectrum of changing geochemical conditions and processes which can affect both hydrocarbon migration and reservoir properties. Post-depositional reactions such as dissolution and precipitation are mediated by chemically distinct fluids that impart their geochemical signature on precipitating mineral phases. Trace element geochemistry and stable isotope analysis can be used to characterize carbonate cement types present in burial sequences of Hibernia and Jeanne d'Arc sandstones and to investigate the chemical nature of the fluids from which these cements were precipitated.

The application of trace element distribution to approximate the chemical composition of diagenetic waters is governed by the homogeneous distribution coefficient D (Kinsman, 1969):

$(\text{Me}/\text{Ca})_s = D_w (\text{Me}/\text{Ca})_w$, where "m" indicates molar concentration, "Me" represents trace element, "s" refers to the solid phase and "w" to the water. This equation is valid only for systems that are at equilibrium; that is the water and solid phase do not show any concentration gradients in the trace element distribution during precipitation and the amount of the solid phase is minor compared to the volume of the circulating fluid system. This ensures that solution composition remains constant (Veizer, 1983).

"Crude" estimates of water compositions can be made using quoted D values and comparing ratios of trace element to Ca in calcite or dolomite with the calculated ratios for marine, meteoric, and subsurface waters. It is important only that the order of magnitude rather than the precise value of the distribution coefficient be known because D 's vary during

precipitation of a single solid phase depending on several physio-chemical conditions such as solution and solid phase composition, precipitation and burial rates, and temperature (Veizer, 1983; Hendry and Marshall 1991).

Knowledge of stable carbon and oxygen isotopic data can constrain chemical conditions under which carbonate mineral phases were precipitated. The oxygen isotopic composition of carbonates forming under equilibrium conditions is a function of the isotopic composition and temperature of the fluid and the fractionation factor (α) between the fluid and solid. Fluids within a sedimentary basin are characterized by their oxygen isotopic composition which may be affected by exchange with carbonate minerals and fractionation across membranes. Carbon isotope data may be used to determine the possible origin of carbonate cements. There are two main carbon reservoirs, organic matter and sedimentary carbonates which differ isotopically from one another. Light ^{12}C is concentrated in organic material (biogenically reduced carbon compounds) whereas bicarbonate is enriched in ^{13}C . Isotopic fractionation occurs between carbonate mineral phases and CO_2 , with possible (significant) fractionation occurring between decay products of the carbonates and CO_2 formed during decarbonatization and the decay products of the organic material, CH_4 and CO_2 (Hoefs, 1987).

5.2 Evaluation of Chemical Data

Two potential problems arise in the interpretation of trace element distribution as a result of the techniques employed. First, bulk analysis as opposed to the physical separation of individual dolomite rhombs or calcite crystals was performed because of the inherent difficulty in

separating individual cement phases. Therefore in certain instances results may reflect an "average" composition of more than one cement generation, resulting from evolving pore fluids that moved through permeable units. More importantly, the possibility of mixing between two or more carbonate mineral phases influences both trace element and isotope analysis. As shown in Table 5.1 (and corroborated for some by XRD shown in Appendix 3), cogenetic precipitation or separate phases of dolomite, calcite, ankerite and siderite occurred in selected samples chosen for study. These, together with other anomalous samples were ignored in subsequent interpretative evaluations.

Both Hibernia and Jeanne d'Arc sandstones show evidence of secondary solution fronts where areas of secondary porosity occur adjacent to tightly carbonate cemented areas. As dissolution proceeded and porosity developed by mesogenetic leaching of carbonate cements and or fossil fragments, interstitial fluids could have become enriched in dissolved ions (Ca^{2+} , Mg^{2+} , Sr^{2+} , Fe^{2+} for example), providing a source for these constituents during later precipitation elsewhere. This mechanism may account for concentric compositional zoning in some late carbonate cements observed under cathodoluminescence and SEM analyses. For example, some microdolomite rhombs in Terra Nova K-07 and Terra Nova I-97 sandstones exhibit iron concentration gradients in a traverse from the rim (relatively enriched) to the core (relatively depleted) (Plate 20). This zonation reflects the complicated crystallization history of the dolomites under fluctuating conditions.

Compositional concentric zoning within carbonate cements is interpreted in terms of changing chemical compositions and/or redox

conditions of pore fluids from which they precipitated (Meyers, 1989) and rates of precipitation. Some cements exhibit non-concentric zoning (sector zoning) characterized by intracrystal compositional boundaries which are discordant with respect to successive crystal growth layers. Such zoning is not simply related to changes in "bulk" fluid composition during precipitation (Hendry and Marshall, 1991).

The lack of visible concentric zoning in many samples studied suggests but does not prove that the composition of the "bulk" solution did not change during precipitation.

The second potential obstacle concerns the use of acid digestion to separate the carbonate fraction from the silicate portion. Partially soluble minerals, such as pyrite and some authigenic clays, may impart their trace element signature to that calculated for carbonate minerals. Although this contamination or interference by adsorbed trace elements from clays or silicates using techniques similar to those used here is considered volumetrically insignificant by Hutcheon *et al.*, 1985, some of the anomalous results in Table 5.1 may reflect such contamination. To test for potential leaching from the silicate portion of the bulk sample, AAS analysis included examining the proportion of Al in the carbonate fraction. Al was present in negligible quantities (less than 0.03 weight percent).

Although Hibernia and Jeanne d'Arc Formations have similar trace element associations (Table 5.1), three compositional fields are distinguishable by the relative abundances (between fields) of Mg, Fe, Mn and Sr. These profiles, exhibiting non-systematic variations in trace elements include:

Table 5.1 a) Carbonate Cement Geochemistry using AAS

Sample I.D.	Depth (m)	% Ca	% Mg	% Fe	Mn (ppm)	Na (ppm)	Sr (ppm)
Hibernia Samples							
WR-N-22-4	3566.80	39.85	0.10	0.37	2250	600	192
WR-N-22-5	3569.22	36.47	0.17	0.39	2370	345	421
WR-N-22-3-2	3572.70	35.41	0.34	3.28	2328	628	504
WR-N-22-6	3573.00	23.96	0.38	3.05	1327	2756	622
SM-C-13-6-1	4582.90	34.71	0.28	2.76	1060	1474	692
SM-C-13-6-2	4585.33	35.53	0.36	3.10	2611	1330	1026
Jeanne d'Arc Samples							
TN-H-99-1-3	3229.95	34.37	0.30	0.19	447	1248	611
TN-H-99-2-7	3243.45	31.39	0.17	0.07	978	697	525
TN-H-99-3-12	3263.42	43.75	0.25	0.13	1127	226	523
TN-K-18-2-2	3221.90	34.59	5.36	2.29	1593	5480	647
TN-K-18-3	3256.50	25.13	2.29	9.45	2975	3960	363
TN-K-18-4	3262.40	34.38	1.66	1.81	2110	300	205
TN-K-18-6-2	3262.60	33.04	1.46	2.15	1749	401	173
TN-K-18-6	3265.60	31.55	7.56	8.32	3705	695	174
TN-K-18-7-2	3268.72	19.84	7.21	10.16	2338	2969	181
TN-K-18-7	3270.30	23.75	7.14	7.48	2090	1350	126
TN-K-18-8	3283.60	22.58	7.59	7.18	2185	790	68
TN-K-18-9	3284.85	23.76	7.91	6.24	2180	350	104
TN-K-18-11-2	3319.93	21.57	7.89	7.60	1908	600	210
TN-I-97-12	3326.00	27.20	8.47	0.41	693	328	252
TN-I-97-5	3311.30	21.84	11.77	0.31	672	621	205
TN-I-97-8	3315.60	18.28	11.34	0.17	821	513	152
TN-I-97-10	3323.20	21.14	11.85	0.39	692	462	202
TN-H-99-3-10	3260.68	22.04	11.14	3.21	1814	729	163

Note: Shaded areas indicate analysis performed on more than one carbonate cement phase. These samples were not used for interpretation.

Table 5.1 b): Re-calculated Carbonate Cement Geochemistry

Sample I.D.	Depth (m)	Soluble Weight (g)	CaCO ₃ (Weight %)	MgCO ₃ (Weight %)	FeCO ₃ (Weight %)	Mn (ppm)	Na (ppm)	Sr (ppm)
Calcite								
WR-N-22-4	3566.80	0.406	98.3	0.4	0.7	2250	600	192
WR-N-22-5	3569.22	0.338	97.8	0.7	0.7	2370	345	421
WR-N-22-3-2	3572.70	0.335	91.6	1.5	6.1	2328	628	504
SM-C-13-6-1	4582.90	0.210	92.5	1.2	5.3	1060	1474	692
SM-C-13-6-2	4585.33	0.153	91.5	1.5	5.7	2611	1330	1026
TN-H-99-1-3	3229.95	0.276	97.4	1.4	0.4	447	1248	611
TN-H-99-2-7	3243.45	0.340	98.3	0.9	0.2	978	697	525
TN-H-99-3-12	3263.42	0.377	98.5	0.9	0.2	1127	226	523
Ferroan Dolomite								
TN-K-18-7-2	3268.72	0.430	49.8	29.9	18.5	2338	2969	181
TN-K-18-7	3270.30	0.327	57.4	28.5	13.1	2090	1350	126
TN-K-18-8	3283.60	0.413	55.6	30.9	12.8	2185	790	68
TN-K-18-9	3284.85	0.401	57.1	31.4	10.9	2180	350	104
TN-K-18-11-2	3319.93	0.330	53.4	32.3	13.7	1908	600	210
Dolomite								
TN-I-97-5	3311.30	0.362	52.4	46.7	0.5	672	621	205
TN-I-97-8	3315.60	0.511	49.0	50.2	0.3	821	513	152
TN-I-97-10	3323.20	0.470	51.4	47.6	0.7	692	462	202
TN-H-99-3-10	3260.68	0.444	51.2	42.8	5.4	1814	729	163

The carbonate mineral phase dissolved is indicated (calcite or dolomite)

All cations are calculated in weight percent carbonate.

Soluble weight: +/- 0.005

1. Field 1: characterized by comparatively higher concentrations of Sr and Mn, average Fe and Na concentrations and low Mg concentrations;
2. Field 2: distinguished by moderately high Na concentrations, high Mg, Fe and Mn contents and low to moderate Sr concentrations.
3. Field 3: high in Mg and relatively low in Na, Fe, Sr and Mn.

5.2.1 Major Elements: Calcium and Magnesium

Deltaic Hibernia and alluvial fan Jeanne d'Arc sandstones were initially deposited with high pre-cement porosities which was later severely reduced by mesogenetic precipitation of calcite and dolomite cements.

The differences in cement constituents is reflected in weight percent cation carbonate content (Table 5.1) of samples and amounts of trace elements. Samples with low weight % $MgCO_3$ (Field 1), are associated with the high Ca concentrations (over 90% $CaCO_3$) and are interpreted as low-Mg calcites. Some of these are ferroan. Samples with $MgCO_3$ weight percent concentrations greater than 40% (field 3) have the lowest Ca concentrations and are treated as dolomites. Cements with intermediate $MgCO_3$ weight percentages (approximately 30% Field 2) also contain relatively high Fe concentrations and are classified as ferroan or ankeritic dolomites (Figure 5.1).

Jeanne d'Arc Formation carbonate cements fall into all three compositional ranges, described above. The cement types appear to be partially correlatable with individual wells. For the Terra Nova wells

Figure 5.1: Mg and Ca

Figure 5.1: The graphical representation of weight percent Mg and Ca carbonate defines three compositional fields for Hibernia and Jeanne d'Arc carbonates. Field 1 is characterized by low weight percent MgCO_3 , and represents low-Mg calcites whereas Field 2 and Field 3 are characterized by higher weight percents of MgCO_3 , and represent dolomites. The lower weight percent of MgCO_3 , in Field 2 is attributed to the presence of iron.

studied, for example TN-I-97 is dolomite cemented (Field 3) whereas TN-H-99 is calcite cemented (Field 1) and TN-K-18 is cemented by ferroan dolomites (Field 2).

In contrast, the Hibernia Formation carbonate samples analyzed are all calcite cemented. These results suggest sampling bias because dolomite cements have earlier been recognized in the Hibernia Formation in the Hibernia oil field (Abid, 1988). Further investigation is required to demonstrate whether calcite is the principal carbonate cement identified in this formation elsewhere outside of the main Hibernia field.

5.2.2 Minor and Trace Elements

Minor and trace elements, particularly Fe, Mn, Na and Sr may substitute for major elements in the lattices of calcite and dolomite following the rules of crystallographic substitution (Day, 1963; Veizer, 1983). Cations with a radius larger than Ca^{2+} will tend to substitute for calcium in the carbonate lattice, and cations with smaller radii for magnesium. The repartitioning of trace elements from metastable to stable phases is controlled by precursor mineralogy and certain elements tend to be closely associated because of similar mobility within a range of environments. Consequently the ratio between such elements remains relatively constant. Sr and Na, in the samples studied, show a relatively strong geochemical coherence with Ca as do Fe and Mn with Mg.

Iron is the most abundant element substituting for Ca and Mg in the carbonate lattice of calcites and dolomites. The low concentration of Fe^{2+} in Jeanne d'Arc and some Hibernia calcites and some Jeanne d'Arc dolomites (Figure 5.2) signifies that conditions for precipitation of these cements

Figure 5.2: Ca, Mg and Fe

Figure 5.2: The weight percent FeCO_3 is lower in non-ferroan dolomites (Field 3) and calcites (Field 1) than in ferroan dolomites (Field 2).

were either highly oxygenated or deficient in Fe.

Early ferroan and non-ferroan calcites occur in the Hibernia Formation whereas only early non-ferroan calcites are observed in the Jeanne d'Arc Formation. Petrographic evidence suggests that the iron-rich cements were precipitated after some mechanical compaction had occurred, therefore prevailing near-surface redox conditions of bacterial oxidation/sulphate reduction which influence variations in both Mn^{2+} and Fe^{2+} were not operative during precipitation of these cements.

Deep meteoric flushing, which may reach depths of 2 km (Galloway, 1984) could have affected the Jeanne d'Arc Formation during periods of uplift, but is not considered to be exclusively responsible for the observed variations of these two cations (see discussion in section 5.4.2).

There is a weakly covarying trend between Fe and Mn concentrations in all cement types (Figure 5.3). Early calcites having low Fe and variable Mn concentrations, may represent precipitation from pore fluids that contained these elements in their non-reduced valence states and consequently limited substitutions for Ca or Mg in the carbonate lattice. This may be related to decarboxylation reactions or oxidizing conditions which prevented the mobilization of Fe. Early Hibernia calcites having relatively high Fe and Mn concentrations may have formed from the reduction of reactive detrital phases during decarboxylation reactions.

Some ferroan dolomites have comparatively high Mn concentrations. Petrographic evidence suggests formation of these cements at considerable depth; therefore the enrichment of both Fe and Mn may be related to deep burial diagenesis involving organic material and clays. During clay

Figure 5.3: There is a covarying relationship between Mn and Fe concentrations in the carbonate lattice. The highest Mn and Fe concentrations are associated with ferroan dolomites in Field 2.

2 of/de 2

PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

PRECISIONSM RESOLUTION TARGETS

diagenesis, at high pressure and temperatures, organic material first reduces all the available MnO_2 , releasing Mn^{2+} , then reduces Fe_2O_3 , releasing Fe^{2+} , resulting in low Mn/Fe ratios.

Sr and Ca concentrations are commonly inversely related because Sr substitutes mostly in the calcium lattice positions of calcite and dolomite (Kinsman, 1969). The extent of Sr^{2+} substitution for Ca^{2+} in carbonate minerals therefore depends, in part, on the relative proportion of calcite to dolomite or Ca to Mg, resulting in relatively high Sr/Ca ratios associated with calcites and relatively low Sr/Ca ratios in both ferroan and non-ferroan dolomites.

Sodium, the most abundant cation in seawater and in most diagenetic solutions, is a common contaminant in AAS analyses. Because there is no theoretical correlation between Na and Mg concentrations, coexisting calcite and dolomite should have similar Na content based on the common distribution law (Land and Hoops, 1973; Veizer, 1983). This is revealed in Jeanne d'Arc non-ferroan dolomites (low Fe and Mn) with low Na concentrations and ferroan dolomites and calcites with slightly higher Na concentrations, both subject to considerable variation.

Na/Ca ratios show no distinctive trend and are probably not a good indicator for fluid composition. Some measured sodium values in both Hibernia and Jeanne d'Arc Formations are significantly higher than what would be expected from equilibrium Na values calculated for theoretical fluids. These local anomalous Na concentrations may be the result dissolution of nearby salts as noted in the shallowest reservoir (Lower Cretaceous Avalon sands) of the Hibernia oil field (Benteau and Sheppard, 1982 cited in Hutcheon *et al.*, 1985). Anomalous Na contents in both Jeanne

d'Arc and Hibernia carbonates could also indicate contamination from other sources, including laboratory digestion of unusual sample constituents.

Katz (1972) suggested that dolomite crystals acquire Na⁺ during crystallization in three different forms:

1. NaCl as dry or liquid inclusions,
2. Na exchange for Ca and Mg in the dolomite lattice sites during crystal growth and
3. Na associated with mineralogical impurities such as clays inherited from original sediment which has been dolomitized, the Na enrichment being due to the exchange of Na and K on clay minerals by membrane filtration.

5.3 Fluid Composition

Mg, Fe, Mn and Sr equilibrium concentrations for theoretical Jeanne d'Arc waters, from which calcites were precipitated, were calculated and then compared with those of present day marine, stream, shallow subsurface and oil waters (Majid and Veizer, 1986) (Table 5.2). Results do not show direct correspondence between any of these waters and calcites. Calculated equilibrium concentrations for Fe and Mn appear to preclude precipitation solely from normal seawater or stream water. The lack of agreement between experimentally calculated and theoretical values may suggest fluid interaction and mixing occurred or that the calcites were precipitated from altered seawater-freshwater, subsurface brines or meteoric flushing.

The approach used for calcites was not used in determining equilibrium concentrations for fluids from which ferroan and non-ferroan

Table 5.2: Equilibrium Concentrations of Cations in Fluids

Me	* D(Me)	Av. Me Conc.	Calc. Me/Ca water	ocean	stream	shallow subsurface	oil
Ca							
Mg	0.06	2383	0.1794088	7.5	0.8	0.9	0.45
Fe	20	1290	1.2680E-04	0.0000038	0.0022	0.006	0.001
Sr	0.14	553	4.9498E-03	0.009	0.002	0.0075	0.035
Mn	15	850	1.1334E-04	0.0000004	0.00035	0.001	0.00035
Na	2.0000E-05	724	172.81	7.5	1	2	9

* D values from Majid and Veizer (1986)

Note: Because of the problems associated with distribution coefficients only the order of magnitude of the equilibrium cation concentrations for theoretical fluids precipitating calcite should be considered.

dolomites were precipitated because distribution coefficients are even more uncertain for carbonates other than calcites.

Several problems are associated with the distribution coefficient for Mg used in calculating equilibrium Mg concentrations. First, extensive experimental work has shown that D_{Mg} is not a constant but varies with temperature and the Mg/Ca ratio of the parent solution. As result a single D value cannot be assigned over a broad range of pore-water compositions (Mucci 1987). The calculation of Mg content in pore fluids is further complicated by the need to estimate D_{Mg} because it is less well known for carbonates other than calcite (Kretz, 1982; Veizer, 1983). Secondly, it is likely that a considerable portion of the Mg in Jeanne d'Arc sandstones is present as disseminated dolomite rhombs and not dispersed in massive carbonate cements.

The calculation of the equilibrium Sr concentrations is also difficult because D_{Sr} varies with rate of precipitation, Mg content of calcite, Sr/Ca content of the solution as well as temperature (Lorenz, 1981; Pingitore and Eastman, 1986; Mucci 1986; Mucci and Morse 1983; refs. cited in Budd and Land, 1990).

5.4 Stable Isotopes

The carbon isotopic reservoir is much smaller than the oxygen isotopic reservoir and equilibrates rapidly with respect to the isotopic composition of the rock during any rock-water interaction (Lohmann, 1983). Several factors control the isotopic composition of carbonate cements including: temperature of precipitation and isotopic composition of fluids. Stable isotope data for selected samples (Table 5.3) are

Table 5.3: Stable Isotopic Composition of Hibernia and Jeanne d'Arc Carbonates

Sample I.D.	Depth (m)	permil 18 O SMOW	permil 0 18 PDB	permil 13 C PDB
Hibernia Samples				
WR-N-22-5	3569.22	24.90	-5.79	-3.24
WR-N-22-3-2	3572.70	24.56	-6.12	-2.09
SM-C-13-6-1	4582.90	24.14	-6.52	-2.20
SM-C-13-6-2	4585.33	22.04	-8.56	-10.02
WR-N-22-4	3566.80	24.61	-6.07	-2.87
Jeanne d'Arc Samples				
TN-K-18-6	3265.60	25.66	-5.05	-7.94
TN-K-18-7-2	3268.72	26.81	-3.94	-5.34
TN-K-18-8	3283.60	25.12	-5.57	-5.93
TN-K-18-11-2	3319.93	25.42	-5.28	-4.57
TN-H-99-1-3	3229.95	26.29	-4.44	-4.90
TN-H-99-3-10	3260.68	25.61	-5.09	-4.77
TN-H-99-3-12	3263.42	26.10	-4.62	-1.01

represented graphically on a $\delta^{13}\text{C}$ versus $\delta^{18}\text{O}$ plot (Figure 5.4).

Calcite and dolomite cements occupy distinct fields, suggesting different temperatures of formation and/or pore fluid composition. There appears to be an overall trend towards lighter carbon and lighter oxygen isotopes with burial diagenesis.

5.4.1 Carbon Isotopes

There are four possible major sources of early calcite in the Jeanne d'Arc and Hibernia Formations: dissolution and reprecipitation of carbonate from fossils or limestone clasts in sandstones and nearby shales; percolating meteoric waters supersaturated with respect to calcite; upward migrating pore fluids experiencing decreasing PCO_2 and decreasing calcite solubility; and carbonates generated in sulphate reduction zones (Boles, 1978; Surdam and Boles, 1979). Later carbonates may be formed by diagenetic reactions in more deeply buried shales and by decarboxylation reactions that produce light carbonates.

Carbonate cements are volumetrically significant in both formations, where an adequate internal source of carbonate is not readily evident. The occurrence of those carbonate cements in sandstones lacking fossil and limestone fragments (especially in the Jeanne d'Arc Formation) is a result of either redistribution within the sandstones or due to the presence of an external source, which may be constrained by the carbon isotopic data.

The overall reaction of carbonate precipitation, either abiotically or by biological consumption is given by:

Figure 5.4: Stable Isotopes

■ Jeanne d'Arc Formation
 □ Hibernia Formation
 Figure 5.4: Carbon and oxygen isotope values for the carbonate cements from Hibernia and Jeanne d'Arc sandstones. Early and late calcites are distinguished by their isotopic composition from dolomites.

Two processes influencing the carbon isotopic signature of Hibernia and Jeanne d'Arc carbonate cements include the decomposition of organic matter in sediments, which consumes oxygen and releases isotopically light CO_2 , and the dissolution of carbonates which adds isotopically heavy CO_2 .

The $\delta^{13}\text{C}$ -values of ferroan and non-ferroan Hibernia calcites show little variance, forming a relatively tight cluster (except for SM-C-13-6-2), ranging from -2.09 to -3.24 permil, with an average of -3.63 permil, which indicate similar temperatures and pore fluid compositions during precipitation of each of the wells studied. Although non-ferroan calcite is abundant in Hibernia samples where calcareous fossil fragments are also locally abundant, an external source is probably also required. Infiltration of meteoric water or formation fluids travelling along the mid-Cretaceous unconformity or along faults may have combined with upward moving fluids derived from deeper compacting calcareous marine units to produce isotopically light CO_2 .

Early ferroan calcites in the Hibernia Formation are commonly associated with early pyrite which is consistent with ferric iron reduction followed by or associated with sulphate reduction. An alternative explanation is precipitation of these cements from warm basinal waters that contain appreciable iron as a result of clay mineral reactions in adjacent shales.

The anomalous Hibernia ferroan calcite (SM-C-13-6-2) with a carbon isotopic composition of -10.00 permil, is a strong indication of the incorporation of substantial amounts of organically derived light carbon. $\delta^{13}\text{C}$ depleted cements formed during burial diagenesis may result from either microbial oxidation of organic matter associated with sulphate

reduction or from thermal decarboxylation of organic matter in interbedded or lower shales, with each process operating at different depths (Irwin et al, 1977). The amount and distribution of organic matter also influences carbonatization reactions.

The carbon isotopic composition of bicarbonate from sulphate reduction and CO_2 from decarboxylation reactions can range up to -25 permil. Therefore it is plausible that mixing between one of these sources and a source characterized by heavier isotopic compositions (such as fluids containing dissolved, isotopically heavy carbonate cements) contributed to the $\delta^{13}\text{C}$ of both Hibernia and Jeanne d'Arc calcites. A possible combination of organic and inorganic carbon results in carbon isotopic values between 0 and -26 permil and may be responsible for the observed $\delta^{13}\text{C}$ values in calcites.

Early non-ferroan calcites of the Jeanne d'Arc Formation have $\delta^{13}\text{C}$ -values ranging from -4.90 to -1.01 permil which suggests a marine source with either a minor contribution from the oxidation of organic matter and sulphate reduction (as indicated by abundant pyrite in Terra Nova wells) or decarboxylation reactions originating from deeper shales.

Ferroan dolomite cements of the Jeanne d'Arc Formation have small negative $\delta^{13}\text{C}$ -values. It is unlikely that these ^{13}C values can be attributed to near surface processes such as microbial oxidation of organic matter and sulphate reduction because these cements are interpreted to have precipitated at depth.

The negative $\delta^{13}\text{C}$ values of calcite and dolomite cements probably reflect a marine carbon source with more negative values indicating a minor input from organic carbon.

5.4.2 Oxygen Isotopes

All samples are relatively depleted in $\delta^{18}\text{O}$ -values, suggesting a strong temperature influence or diagenetic fluids depleted $\delta^{18}\text{O}$. Early Hibernia calcites show little variation in $\delta^{18}\text{O}$ values (average of -6.20 permil PDB) with a maximum difference of 1.70 permil PDB, indicating either similar temperatures of formation for all wells studied or the uniform influence of isotopically light waters. Jeanne d'Arc early non-ferroan calcites are heavier, with an average $\delta^{18}\text{O}$ value of -4.53 permil PDB and even less variation (maximum difference of 0.18 permil PDB).

To evaluate the influence of meteoric water versus temperature on the geochemical nature of the cements, ratios of Sr/Ca and Mn/Ca were plotted with respect to the oxygen isotopic composition of the cements (Figure 5.5). If light $\delta^{18}\text{O}$ values of the cements are the result of meteoric water, a decrease in Sr/Ca ratio with corresponding increase in Mn/Ca ratio should accompany more negative $\delta^{18}\text{O}$ values (Hutcheon *et al.*, 1985). As shown in Figure 5.5 the contrary is apparent. Therefore it seems more probable that lighter oxygen isotopic values are the result from elevated temperatures, from deep basinal or rising warm waters or from mixing of pore fluids rather than the exclusive influence of meteoric waters.

5.5 Chemical Constraints

To determine either the isotopic composition of the fluids from which Jeanne d'Arc and Hibernia calcites were precipitated or the temperature at which the minerals formed (in the absence of mineral pairs) an assumption must be made with respect to one of these variables. Various fluid isotopic compositions (relative to SMOW) and temperatures

Figure 5.5 a) Sr/Ca versus Permil 18 O

Figure 5.5 b) Mn/Ca and Permil 18 O

Figure 5.5: Sr/Ca and Mn/Ca ratios versus $\delta^{18}\text{O}$ indicates that meteoric water is not solely responsible for the geochemical characteristics of the cements. Sr/Ca ratios (a) would decrease with lighter $\delta^{18}\text{O}$ whereas Mn/Ca ratios (b) would decrease.

were calculated using the formula of O'Neill et al (1969). From interpretations discussed above, mixing of fluids from two sources may have been responsible for the isotopic character of the calcite cements. Calculations of temperature vs $\delta^{18}\text{O}$ ((SMOW) of the fluid, suggest that because the fluids are depleted in ^{18}O (meteoric or warm basinal fluids) a temperature of 60 degrees Celsius or less is required for early calcite precipitation.

Jeanne d'Arc dolomites are depleted in ^{18}O , with a mean $\delta^{18}\text{O}$ of -4.98 permil FDB. If the pore water responsible for the precipitation of dolomite was similar to that of Jurassic sea water, then the oxygen isotopic composition of the dolomite would be approximately +1 (assuming the average $\delta^{18}\text{O}$ of Jurassic marine calcites is about -2 permil (Veizer, 1983)). Because much lighter values are evident and because of the iron-rich character of the dolomites, precipitation and/or recrystallization at somewhat elevated temperatures is conceivable. The possible addition of bicarbonate, Ca and Mg ions to fluids expelled from underlying/interbedded compacting shales (perhaps aided by high hydraulic head in the tectonic uplands) may have promoted precipitation. Another possibility may involve mixing between deeply penetrating meteoric water circulation derived from uplifted areas to the east of the Jeanne d'Arc Basin (Outer Ridge Complex) and pore fluids derived from underlying overpressured shales.

5.6 Summary of Isotopic Data

When stable isotopic data are combined with previous studies on the Jeanne d'Arc Basin, at least four fields can be delineated (Figure 5.6).

Figure 5.6: Jeanne d'Arc Basin

Figure 5.6: Carbon and oxygen isotopic composition of carbonate cements from the reservoir sandstones of the Hibernia field (Abid, 1988) were compared with Jeanne d'Arc and Hibernia sandstones in this study, showing reasonably good correlation.

Early calcites show the heaviest carbon isotopic composition while late calcites are the most depleted in $\delta^{13}\text{C}$. In addition, early and late calcites have lighter $\delta^{18}\text{O}$ values than early and late dolomite cements. There is a shift towards lighter carbon and oxygen isotopes in Hibernia and Jeanne d'Arc calcites (from early to late). A similar negative shift is noticed in oxygen isotopic composition of Jeanne d'Arc Mg-rich carbonates.

Chapter 6: Conclusions

This study used petrographical observations augmented by geochemical analysis to interpret the diagenetic history of the Jeanne d'Arc Formation sandstones. A limited number of sandstones were also investigated from the Hibernia Formation to compare the reservoir characteristics and burial histories of the two formations.

The main conclusions of this study are:

1. A distinctive feature of both the Hibernia and Jeanne d'Arc Formations is their simple detrital mineralogy. Sandstones from both units are clean (having very low matrix material) and mainly plot as sublitharenites and quartz arenites (Folk, 1974). The average framework grain composition of the Jeanne d'Arc and Hibernia Formations are $Q_{40}F_{40}R_{20}$ and $Q_{40}F_{40}R_{20}$, respectively.

2. Present porosity and pre-cement porosities are higher in the Jeanne d'Arc Formation than in the Hibernia Formation. Based on present day porosities and assuming sands were deposited with an original porosity of 40%, there was a 12% loss of porosity due to compaction in the Jeanne d'Arc Formation compared to a 16% loss in the Hibernia Formation. Porosity reduction due to compaction does not appear to be related to depth as suggested by the advanced compaction of the younger Hibernia Formation. Therefore it seems likely that many of the reservoir sandstones studied from the Hibernia Formation escaped early cementation or that early cementation was not complete. Undercompacted sandstones in the Jeanne d'Arc sandstones contributed to the preservation of the bulk of the porosity and may be related to the position of the sandstones in an overpressure zone.

3. The relative amount of porosity lost due to cementation after compaction is similar in both formations, based on evidence in this study. However, because of the limited number of Hibernia samples, this result may show bias, although it appears that cementation was more important in reducing porosity in the Jeanne d'Arc Formation than in the Hibernia Formation.

4. Jeanne d'Arc compaction curves (based on the Sclater-Christie model) show that many of the sandstones are undercompacted, suggesting early cementation; this is also shown by high pre-cement porosities.

5. The study of interfaces between tightly cemented sandstones and adjacent more porous regions suggest they are most likely dissolution boundaries when they are irregular and gradational. Similar textural features are observed on either side of the boundaries and across the transition zones. Abrupt boundaries are more likely precipitation fronts (representing prior dissolution elsewhere followed by removal and transport of minerals in solution and subsequent reprecipitation at the contact).

6. Porosity enhancement was largely controlled by decarbonatization rather than framework grain dissolution in both formations, as indicated at dissolution contacts between tightly cemented and porous areas, and relative proportions of dissolved framework grains and other types of secondary porosity.

7. Geochemical analyses on the carbonate cements from the Hibernia Formation indicate that the cements are ferroan and non-ferroan calcites. Jeanne d'Arc cements show heterogeneity both within their crystal lattice and their cement composition (dolomites and calcites).

8. Three carbonate cement types are recognized in the Jeanne d'Arc Formation, based on AAS analysis of Ca, Mg, Fe, Sr, Na and Mn: non-ferroan calcites, ferroan dolomites and non-ferroan dolomites.

9. In the Jeanne d'Arc Formation, the presence of zoned (post-dissolution) dolomite rhombs showing Fe concentration gradients within their crystal structure suggests that the chemistry of the circulating fluids was changeable at least locally. This may be related to the variability of Jeanne d'Arc carbonate cements as preferential leaching of some elements occurred.

10. Stable carbon and oxygen isotopes studies on the carbonate cements from both formations show that the chemically distinguishable compositional groups also occupy distinct isotopic fields.

Chapter 7: Suggestions For Further Work

This study was primarily interested in sandstone reservoir properties as investigate through the diagenetic history of the Jeanne d'Arc Formation. To augment this study of petrography, sandstone burial process and carbonate cement geochemistry, further research may include:

1. Fluid inclusion studies on carbonate cements and quartz overgrowths: Geothermometric studies of aqueous and possible oil inclusions in carbonate cements would provide minimum crystallization temperatures of the host and a measure of solution salinity. Used with stable isotope data and petrographic information, an additional control on the sequence and timing of authigenic minerals could be established, along with considerations regarding pore fluid chemistry.

2. Organic geochemistry on interbedded shales including: total organic content, kerogen type and vitrinite reflectance. Organic matter content would determine the amount of carbon dioxide and complexing agents that are produced which is related to the amount of dissolution and hydrocarbons generated. Vitrinite reflectance, thermal history of the Jeanne d'Arc Basin. As a result a comprehensive diagenetic model would be established, confirming the importance of shale diagenetic reactions on interbedded sandstone reservoirs.

3. Further investigation (petrographic and chemical) of wells penetrating the Hibernia and Jeanne d'Arc Formations outside the Hibernia and Terra Nova fields to establish th lateral variations of burial diagenesis within the Jeanne d'Arc Basin.

4. The oxygen isotopic composition of quartz overgrowths, although difficult to determine when they constitute less than 10% of the rock, would

enable temperature of early carbonate precipitation. A plot of the average value of quartz overgrowths as a function of temperature and the oxygen isotopic composition of water would constrain the conditions under which the overgrowths formed. Similarly, the oxygen isotopic composition of other authigenic components such as clays would provide temperature estimates of authigenic phases that predate and postdate secondary porosity development, giving better interpretation of the timing of diagenetic events.

5. Complete chemical analysis of present day formation waters including trace element concentrations, oxygen and hydrogen isotopic data and calculation of calcite saturation indices would complement petrographic data giving insight into in-situ pH and relative minerals solubilities.

6. The examination of carbon dioxide in the associated natural gases of hydrocarbon reservoirs would help in investigating the importance of the gas in dissolving surface fluids.

7. Comparison of calculated temperatures from isotopic data with measured bore hole temperatures would place temperature constraints in the formation of authigenic phases.

8. Regional (contour) mapping of the sandstone/shale ratios to determine their relationship to shale diagenesis and sandstone burial histories.

***All plates from the Jeanne d'Arc Formation, unless otherwise stated. Bar scale on core photos is in centimetres.**

Plate 1

Upper: A medium-grained, moderately well sorted sandstone showing an oversized, irregular pore formed as a result of almost completely dissolution of a framework grain (f) above an elongate pore (e). Also note corroded quartz grain boundaries. TN-I-97-4, 3304.50m, width of field 0.6mm, plane polarized light.

**Lower: Drill core Terra Nova C-09 showing an abrupt contact between a silty shale and an overlying coarse-grained, oil-stained, porous sandstone.
3466.87m.**

Plate 2

Upper: Drill core Terra Nova E-79. Porous oil-stained, fine-grained, cross-bedded sandstone overlies dolomite-cemented, medium grained sandstone with carbonaceous wisps and pyrite aggregates (b). 3228.50m.

Lower: Drill core medium-grained sandstone Terra Nova E-79 showing low angle cross bedding capped by horizontal, argillaceous laminae at the top of the section (a). Also note pyrite aggregate parallel (p) to cross-laminae. 3283.0m.

Plate 3

Upper: Drill core Terra Nova C-09 showing fine-grained, dolomite-cemented sandstone with discontinuous, wavy shaly partings (s) and argillaceous wisps outlining cross-laminae. 3475.06m.

Lower: Drill core of medium grained, slightly calcareous sandstone with soft, ovoid mud rip-up clasts (m). The distorted, irregular shapes of some clasts have been produced by mechanical compaction. TN-C-09, 3483.40m

Plate 4

Upper: Drill core, poorly sorted, coarse-grained to pebbly sandstone, with large light brown ironstone nodule (n), carbonaceous wisps (c) and red jasper pebble (j). Terra Nova E-79, 3229.70m.

Lower: Drill core Terra Nova E-79 showing medium-grained sandstone with irregular distribution of dolomite cement (d). Note the boundary between the porous (p) and carbonate cemented areas is diffuse but clearly distinguishable. Also present are argillaceous partings (a) and laminae (p). 3303.60m

Plate 5

Upper: Drill core of medium to coarse-grained sandstone from Terra Nova H-99 (3257.0m). Note the gradational contact (g) between the tightly dolomite cemented medium grained sandstone and the porous coarser grained sandstone at the bottom in comparison to the more abrupt contact (a) at the top. Also evident are rounded, pebble-size chert clasts (c) with partially dissolved grain boundaries in the oil-stained sandstone and few scattered pyrite blebs (p) in the cemented sandstone.

Lower: Very fine-grained, moderately well sorted sandstone showing an abrupt contact between a tightly calcite cemented sand and a porous sand. Remnant patches of carbonate cement are visible in the adjacent porous area. This sample from the Hibernia Formation is composed predominantly of mono-crystalline quartz. WR-J-49-1, 3916.10m, field of view 4.5mm, crossed nicols.

Plate 6

Upper: Drill core, Terra Nova C-09 showing gradational contact between relatively tightly dolomite-cemented, medium-grained sandstone (grey) and more porous medium-grained sandstone (light brown). Some chemical difference within the cemented zone is suggested by the light to darker grey colour transition. 3365.0m

Lower: Drill core of argillaceous siltstone from Terra Nova H-99 showing soft sediment deformation features and convolute bedding (possible bioturbation) near the bottom of the section overlain by cross laminated siltstone and then overlying subhorizontal laminated silt and shale. 3270.16m.

Plate 7

Upper: Drill core of silty shale from Terra Nova C-09. showing ripple cross lamination (r) at the top of the section. 3337.80m.

Lower: Drill core from Terra Nova well C-09 showing a matrix supported polymictic, paraconglomerate. 3384.0m

Plate 8

Upper: Coarse-grained sandstone showing well developed, euhedral syntaxial quartz overgrowths (o) surrounding rounded detrital quartz host (d). Pressure solution features are evident between quartz overgrowths. Note the undulatory extinction (u) (bottom left and top right) typical of many of the polycrystalline quartz grains. Early poikilitopic sparry calcite cement is present (c) and was most likely precipitated at shallow depths as indicated by framework grains floating in the cement. The porosity (p) in this sample (top right) is secondary, as suggested by the corroded and irregular outline of the monocrystalline quartz (mp) which was probably replaced by the carbonate cement that later dissolved. TN-I-97-5, 3311.50m., width of field 1.7mm, crossed nicols.

Lower: Loosely packed, coarse-grained sandstone with remnant patches of carbonate cement (c). The partial dissolution of pore-filling carbonate cement formed irregular, secondary pores (p). Detrital quartz margins and syntaxial overgrowth rims are corroded (arrows) suggesting they were replaced by carbonate cement which later dissolved. Note vacuoles evident in detrital quartz (v) and presence of plagioclase feldspar (f) (lower left). The polycrystalline quartz (pq) in the upper left corner is likely plutonic in origin because it contains less than 10 sub-crystals of subequant shapes with relatively straight inter-crystalline boundaries. TN-I-97-3, 3304.00m, width of field 0.6mm, crossed nicols.

Plate 9

Upper: Coarse-grained sandstone with large metamorphic polycrystalline quartz grain (m) and remnant patches of carbonate cement (c). Mechanical compaction is noted by the presence of a ductile sedimentary rock fragment (mudstone (s)) which has been squeezed between more rigid quartz grains, reducing the porosity around the mudstone. TN-K-18-1, 3204.80m., width of field 0.6mm, crossed nicols.

Lower: Coarse-grained sandstone with angular dark grey fine-grained volcanic clast with quenched feldspar laths. Note embayments of quartz rims (e) and corroded grain boundaries (c) suggesting replacement by and later dissolution of carbonate (dolomite) cements forming secondary pores. Thin syntaxial quartz overgrowths (o) are also almost indistinguishable from their detrital hosts because of the lack of inclusions, clay minerals or iron oxides rimming the particles as a dusty border, thus visibly separating the detrital core from authigenic silica. TN-H-99-3-10, 3260.68m, width of field 4.5mm, crossed nicols.

Plate 10:

Upper: Angular-subrounded, coarse-grained, moderately well sorted, tightly dolomite cemented sandstone. Porosity has been virtually occluded by the precipitation of early, coarse carbonate cement. There is little grain-to-grain contact as the detrital components appear to be "floating" in the carbonate cement. Note the rounded shape of the plagioclase grain (f) near the centre of the photo. Also visible is a sandstone sedimentary rock fragment (r) below the feldspar. This siliceous clast is free of carbonate, unlike the host rock. TN-K-18-8, 3283.60m, width of field 0.6mm, crossed nicols.

Lower: Medium-grained, well sorted sandstone showing evidence of secondary porosity (p) (as a consequence of the dissolution of earlier precipitated carbonate cement). Of special interest is the honey-comb feldspar grain (h) in the centre of the photo which has undergone selective dissolution (crystallographically controlled). Also evident are embayed (e) and corroded (c) quartz boundaries. TN-I-97-4-2, 3317.86m, width of field 4.5mm, crossed nicols.

Plate 11

Upper: Medium to coarse-grained, moderately compacted sandstone with many point contacts between quartz grains. The presence of clay rich matrix (m) material between detrital quartz may have retarded the formation of abundant quartz overgrowths by inhibiting the fluid circulation by reducing porosity and permeability while the precipitation of carbonate cement reduced original porosity and may have occurred after compaction as suggested by the presence of long and concavo-convex grain contacts. TN-H-99-4-13, 3268.87m, width of field 4.5 mm, plane polarized light.

Lower: Medium-grained, moderately well-sorted sandstone containing a number of rock fragments of various lithologies. Two carbonate rock fragments are seen: one is composed of fine-grained calcite with quartz grains (sp) and the other is a micritic calcite (m). A fossil shell fragment (f) (?mollusk) containing holes, possibly caused by boring organisms is not the likely source for the remnant patches of carbonate cement (d). Also visible are a shaly sedimentary rock fragment (s) and sandstone rock fragments (t). TN-K-18-1, 3204.32m, width of field 1.7mm, crossed nicols.

Plate 12

Upper: Medium-grained, moderately well sorted, tightly carbonate (dolomite) cemented sandstone. Note the very fine-grained rock fragment (s) fragment containing quartz and clays that was likely cemented, escaping compaction. Also evident are possibly truncated quartz overgrowths (o) around detrital quartz grains. Pervasive carbonate and silica cementation during early diagenesis occluded most of the original porosity. TN-K-18-1, 3204.80m, width of field 1.7mm, crossed nicols.

Lower: Porous sandstone containing comminuted plant debris (c) which tends to occur as stringers parallel to bedding or as irregular forms. Abundant carbonaceous material is often associated with pyrite. Also evident is matrix material at the lower part of the photo. TN-I-97-5-2, 3324.55m, field of view 4.5mm, plane polarized light.

Plate 13

Upper: Drill core of medium-grained, oil-stained, porous sandstone (p) from Terra Nova C-09 (3364.0m) containing carbonaceous laminae and stringers (c) adjacent to tightly dolomite-cemented (d) sandstone. Core width is approximately 11 cm.

Lower: Medium to coarse grained sandstone showing early poikilitopic calcite cement which reduced original porosity significantly and partially replaced grains along the margins. Compaction was inhibited by cementation as suggested by the point grain contacts. TN-K-18-6-2, 3262.40m, field of view 4.5mm, crossed nicols

Plate 14:

Upper: Loosely packed, medium grained moderately well sorted sandstone with remnant patches of coarse, euhedral, zoned dolomite rhombs (d). Note corroded quartz grain boundaries (c) and partially dissolved feldspar (f). Black areas are a combination of quartz grains in extinction and porosity. TN-H-99-3, 3229.95m, field of view 1.7mm crossed nicols.

Lower: Drill core of dark, mudstone and siltstone facies with rounded siderite nodules (s) from Terra Nova C-09 (3343.0m).

Plate 15

Upper: Sphaerosiderite clast. Note the presence of an early carbonate cement (d) (ferroan dolomite) which has replaced some quartz grains. Also evident are syntaxial quartz overgrowths (o). TN-H-913, 3268.87m, width of field 1.7mm, crossed nicols.

Lower: Very fine-grained, moderately well sorted sandstone from the Hibernia Formation with siderite rich lamina showing characteristic dark brown flattened rhombic morphology. Note the corroded quartz grain boundaries outside of the siderite laminae and the presence of calcite.. WR-J-49-1, 3916.10m, width of field 4.5mm, crossed nicols.

Plate 16:

Upper: SEM photo of a high Mg ferroan dolomite-cemented, coarse-grained, moderately sorted sandstone. Pore (p) partially infilled by kaolinite aggregates (k) which precipitated after the formation of euhedral quartz overgrowths (o). Dolomite rhombs (d) occlude most of the original porosity. TN-K-18-6, 3265.6m, scale shown at base.

Lower: SEM photo of a tightly packed very-fine to fine-grained sandstone from the Hibernia Formation. Loose aggregate of radiating, fibrous, Fe-rich chlorite (c) partially filling a small intergranular pore (p) between quartz grains (q). This clay, rarely observed in both the Hibernia and Jeanne d'Arc Formations, appears as pale green to yellow-green in thin section. WR-N-22-6, 3573.0m, scale shown at base.

Plate 17

Upper: SEM photo of fine-grained, porous, moderately sorted sandstone with little visible carbonate cement. Illite (i) wisps bridging an oversized pore are visible. Poorly developed kaolinite aggregate (k), possibly an alteration product of a feldspar is also evident. Note the detrital quartz grain (q) at the top of the photo. TN-I-97-15, 3327.7m, scale shown at top.

Lower: Drill core of medium-grained oil-stained and dolomite cemented sandstone from Terra Nova C-09. Large pyrite aggregates (p) are randomly dispersed or concentrated along seams parallel to bedding. 3354.10m

Plate 18

Upper: Medium-grained moderately well sorted sandstone showing fair secondary porosity (p) (epoxy stained yellow). Early formed authigenic (eogenetic) euhedral pyrite cubic crystals (y) concentrated in sub-horizontal laminae. TN-I-97-4, 3334.40m, width of field 1.7mm, plane polarized light.

Lower: Irregularly distributed secondary pores. Oversized pore (o) at bottom of photo resulted from framework grain dissolution. Also note partially dissolved fine grained sedimentary rock fragment (s) in the centre of the photo. TN-I-97-5-1, 3314.80m, width of field 1.7mm, plane polarized light.

Plate 19

Upper: Photomicrograph of a typical, very fine-grained sandstone from South Mara C-13 (Hibernia Formation) showing tight packing and the occlusion of original porosity. Pressure solution at quartz grain contacts suggests advanced compaction. 4392.52m, width of field 4.5mm, crossed nicols.

Lower: SEM photograph of a partially dissolved potassic skeletal feldspar grain showing honey-comb texture resulting from selective solution along crystallographic planes. TN-K-19-6. 3265.6m

Plate 20

Upper: Medium-grained sandstone showing relatively good secondary porosity (epoxy-stained yellow) as suggested by numerous quartz embayments and corroded grain boundaries. Also visible is a secondary pore once occupied by a framework grain which has completely dissolved. The opaque mineral outlines the morphology of the original grain boundary but precursor mineralogy is not immediately evident. TN-H-99-1-4. 3233.78m, width of field 1.7mm, plane polarized light.

Lower: SEM photograph showing incongruent dissolution of sodic feldspar. TN-I-97-3.

Plate 21 a)

Upper: SEM photograph of a partially leached microdolomite rhomb with a laminar pore in its outer rim. EDX analysis of the rhomb (Plate 22) indicates that the outer shell is more iron rich relative to the inner core of the rhomb, reflecting the complicated crystallization/dissolution history of the cement. Scale shown at top.

Lower: Remnant dolomite rhomb whose core has been preferentially dissolved. Undissolved calcite is also evident near the core of the rhomb. This compositional variation is suggestive of disequilibrium conditions and changing pore fluid chemistry.

References

- Abid, I. 1988. Mineral diagenesis and porosity evolution in the Hibernia oil field. PhD Thesis. Unpubl., McGill University, Montreal, 280 p.
- Amoco Canada Petroleum Company Ltd. and Imperial Oil Ltd., 1973. Regional geology of the Grand Banks. Bulletin of Canadian Petroleum Geology, v. 21, pp. 479-503.
- Angino, E.E. and Billings, G.K., 1967. Methods in geochemistry and geophysics. New York. Elsevier Publ. Co. 1449p.
- Arthur, K.R., Cole, D.R., Henderson, G.G.L., and Kushnir, D.W., 1982. Geology of the Hibernia Discovery. In The Deliberate Search for the Subtle Trap (eds. Halbouty, M.T.). AAPG Memoir 32, pp. 181-195.
- Avery, M.P., Bell, J.S., and McAlpine, K.D., 1986. Vitritinite reflectance measurements and their implications for oil and gas exploration in the Jeanne d'Arc basin, Grand Banks, eastern Canada. GSC Paper 86-1A, Current Research, Part A, pp. 489-498.
- Baldwin, B., and Butler, C.O., 1985. Compaction Curves. AAPG Bulletin, v. 69, pp. 622-626.
- Beard D.C., and Weyl, P.K., 1973. Influence of texture on porosity and permeability of unconsolidated sand. AAPG Bulletin, v. 57, pp. 349-369.
- Benteau, R.I., and Sheppard, M.G., 1982. Hibernia-a petrographical and geological review. Journal of Canadian Petroleum Technology, v. 21, pp. 59-72.
- Berner, R.A., 1980. Early Diagenesis: a theoretical approach. Princeton, New Jersey: Princeton University Press.
- Bjorlykke, K., 1984. Formation of secondary porosity, how important is it. In Clastic Diagenesis (eds. McDonald, D.A., and Surdam, R.C.); AAPG Memoir 37, pp. 277-286.
- Blatt, H., 1979. Diagenetic processes in sandstones. In Aspects of Diagenesis (eds. Scholle, P. A., and Schluger, P.R.); SEPM, Spec. Publ., 26, pp. 141-157.
- Blatt, H., Middleton, G.V. and Murray, R.C., 1972. Origin of Sedimentary Rocks. Englewood Cliffs, N.J., Prentice Hall, 64p.
- Boles, J.R., 1978. Active ankerite cementation in the subsurface Southwest Texas. Contrib. Mineral. Petrol., v. 49, pp. 55-70.
- Brown, D.M., 1985. Sedimentology of the Upper Jurassic-Lower Cretaceous Hibernia Member of the Missisauga Formation in the Hibernia Oil Field, Jeanne d'Arc Basin. MSc. Thesis, Unpubl., Carleton University, Ottawa, 157p.

Brown, D.M., McAlpine, K.D. and Yole, R.W., 1989. Sedimentology and sandstone diagenesis of Hibernia Formation in Hibernia Oil Field, Grand Banks of Newfoundland. AAPG Bulletin, v. 73, pp. 557-575.

Bruce, C.H., 1984. Smectite dehydration and its relation to structural development and hydrocarbon accumulation in Northern Gulf of Mexico Basin. AAPG Bulletin, v. 68, pp. 673-683.

Budd, D.A. and Land, L.S., 1990. Geochemical imprint of meteoric diagenesis in Holocene ooid sands, Schooner Cays, Bahamas: correlation of calcite cement geochemistry with extant groundwater. Journal of Sedimentary Petrology, v. 60, pp. 361-378.

Cant, D.J., 1986. Diagenetic Traps in sandstones. AAPG Bulletin, v. 70, pp.155-160.

Carver, R.E. 1976. Procedures in sedimentary petrology. New York, Wiley-Interscience, 653 p.

Chamberlain, C.K., 1978. Recognition of trace fossils in cores. In Trace Fossil Concepts. SEPM, Short Course no. 5, pp. 119- 166.

Coniglio, M., James, N.P., and Aissaoui, D.M., 1988. Dolomitization of Miocene carbonates, Gulf of Suez, Egypt. Journal of Sedimentary Petrology, v. 58, pp. 100-119.

Creaney, S., and Allison, B.H., 1987. An organic geochemical model of oil generation in the Avalon/Flemish Pass sub-basins, East Coast Canada. Bulletin of Canadian Petroleum Geologists, v. 35, pp. 12-23.

Curtis, C.D., 1978. Possible links between sandstone diagenesis and depth-related geochemical reactions occurring in enclosing mudstones. Journal of Geological Society of London, v. 135, pp. 107-117.

Damanti, J.F. and Jordan, T.E., 1989. Cementation and compaction history of synorogenic foreland basin sedimentary rocks from Huaco, Argentina. AAPG Bulletin, v. 73, pp. 858-873.

Dapples, E.C., 1967. Diagenesis of sandstones. In Diagenesis in Sediments; Developments in Sedimentology 8 (eds. Larson, G., and Chilingar, G.V.). Elsevier, New York. pp. 91-126.

Day, F.H., 1963. The chemical elements in nature. George G. Harrop and Co. Ltd., 372p.

Das, J.M.A., and Neal, W.J., 1990. Modal size classification of sands: an example from the northern Portugal continental shelf. Journal of Sedimentary Petrology, v. 60, pp. 426-437

Dickson, J.A.D., 1965. A modified staining technique for carbonates in thin section. Nature, v. 205, p.587.

Duane, D.B., 1964. Significance of skewness in recent sediments, western Pamlico Sound, North Carolina. *Journal of Sedimentary Petrology*, v. 34, pp. 864-874.

Dutton, S.P. and Diggs, T.N., 1992. Evolution of porosity and permeability in the lower Cretaceous Travis Peak Formation, East Texas. *AAPG Bulletin*, v. 76, pp. 525-269.

Dwyer, J.D. and Welsink, H.J., 1988. Structural styles and stratigraphy of Terra Nova Oil Field, Grand Banks. Abstract. *AAPG Bulletin*, v. 72, pp. 181.

Enachescu, M.E., 1987. The tectonic and structural framework of the northeast Newfoundland continental margin. *In* *Sedimentary basins and basin-forming mechanisms* (eds. Beaumont, C. and Tankard, A.J.). Canadian Society of Petroleum Geologists Memoir 12, pp. 117-146.

Folk, R.L., 1974. *Petrology of Sedimentary Rocks*. Hemphill Publ. Co., Austin Texas. 182p.

Franklin, S.P. and Tieh, T.T., 1989. Petrography, diagenesis and reservoir properties of the Dakota sandstone of West Lindrith Field, Rio Arriba County, New Mexico. *In* *Petrogenesis and petrophysics of selected reservoirs of the Rocky Mountain region* (ed. Coalson, E.B.). Rocky Mountain Association of Geologists, Denver, pp. 117-133.

Franks, S.G., and Forrester, R.W., 1984. Relationships among secondary porosity, pore-fluid chemistry and carbon dioxide, Texas Gulf Coast. *In* *Clastic Diagenesis* (eds. McDonald, D.A., and Surdam, R.C.); AAPG Memoir 37, pp.63-80.

Friedman, I. and O'Neil, J.R., 1977. Compilation of stable isotope fractionation factors of geochemical interest. U.S. Geol. Sur. Pro. Paper 440-K, 12p.

Friedman, G.M. and Sanders, J.E., 1978. *Principles of Sedimentology*. New York, John Wiley and Sons Publ., 576p.

Fuchtbauer, H., 1967. Influence of different types of diagenesis on sandstone porosity. Seventh World Petrol. Cong. Proc., v. 2, 353-369.

Fuchtbauer, H., 1974. *Sediments and Sedimentary Rocks I*. Stuttgart, E., Schweizerbart'sche Verlagsbuchhandlung, 464p.

Galloway, E., 1984. Hydrologic regimes of sandstone diagenesis. *In* *Clastic Diagenesis* (eds. McDonald, D.A., and Surdam, R.C.); AAPG Memoir 37, pp. 3-14.

- Grant A.C., McAlpine, K.D. and Wade, J.A., 1986. The continental margin of eastern Canada-geological framework and petroleum potential. *In* Future Petroleum Provinces of the World (ed. Halbouty, M.T.). AAPG Memoir 40, pp. 177-205.
- Grant, A.C. and McAlpine, K.D., 1990. The continental margin around Newfoundland. *In* Geology of the Continental Margin of Eastern Canada (eds. Keen, M.J. and Williams, G.L.); Geological Survey of Canada, Geology of Canada, no. 2., pp. 239-292.
- Handyside, D.D., and Chipman, W.I., 1983. A preliminary study of the Hibernia field. *Journal of Canadian Petroleum Technology*, v. 22, pp. 67-78.
- Hayes, J.B., 1979. Sandstone diagenesis - The hole truth. *In* aspects of Diagenesis (eds. Scholle, P.A., and Schluger, P.A.); SEPM, Spec. Publ., 26, pp.127-139.
- Heald, M.T., 1956. Cementation of Simpson and St. Peter sandstones in parts of Oklahoma, Atlanta, and Missouri. *Journal of Geology*, v. 64, pp. 16-30.
- Hendry, J.P. and Marshall J.D., 1991. Disequilibrium trace element partitioning in Jurassic sparry calcite cements: implications for crystal growth mechanism during diagenesis. *Journal of the Geological Society*, London, v. 148, pp. 835-848.
- Hoefs, J., 1987. Stable Isotope Geochemistry. New York, Springer-Verlag, 241p.
- Holland, M.T., 1984. Reservoir porosity implications of pore geometry modification accompanying sand diagenesis: Anahuac Formation, Louisiana. *In* Clastic Diagenesis (eds. McDonald, D.A. and Surdam, R.C.). AAPG Memoir 37, pp. 391-411.
- Hutcheon, I., Nahnybida, C.G., and Krouse, H.R., 1985. The geochemistry of carbonate cements in the Avalon sand, Grand Banks of Newfoundland. *Mineral. Magazine*, v. 49, pp. 457- 467.
- Irwin, H., Coleman, M. and Curtis, C., 1977. Isotopic evidence for the source of diagenetic carbonate during burial of organic-rich sediments. *Nature*. v. 269, pp. 209-213.
- Jansa, L.F., and Wade, J.A., 1975. Geology of the continental margin off Nova Scotia and Newfoundland. *In* Offshore Geology of Eastern Canada; Geological Survey of Canada Paper 74-30, pp. 51-105.
- Kahn, J.S., 1956. The analysis and distribution of the properties of packing in sand-size sediments-1, on the measurement of packing in sandstones. *Journal of Geology*, v. 64, pp. 385-395.

- Katz, A., Sass, E., Starinsky, A. and Holland, H.D., 1956. Strontium behaviour in the aragonite-calcite transformation: an experimental study at 40-90 degrees C. *Geochim Cosmochim. Acta*, v. 36, pp. 481-496. 1972.
- Keen, C.E., Boutilier, B., de Voogd, Mudford, B., and Enachescu, M. . , 1987. Crustal geometry and extensional models for the Grand Banks, eastern Canada: constraints from deep seismic reflection data. *In* *Sedimentary basins and basin-forming mechanisms* (eds. Beaumont, C. and Tankard, A.J.). Canadian Society of Petroleum Geologists Memoir 12, pp. 101-115.
- Kinsman, D.J.J., 1969. Interpretation of Sr^{2+} concentrations in carbonate minerals and rocks. *Journal of Sedimentary Petrology*, v. 39, pp. 486-508.
- Kuehl, S.A., Nittrouer, C.A., and DeMaster, D.J., 1988. Microfabric study of fine grained sediments: observations from the Amazon subaqueous delta. *Journal of Sedimentary Petrology*, v. 58, pp. 12-23.
- Land, L.S. and Hoops, G.K., 1973. Sodium in carbonate sediments and rocks. A possible index to the salinity of diagenetic solutions. *Journal of Sedimentary Petrology*, v. 43, pp. 614-617.
- Land, L.S., 1984. Frio sandstone diagenesis, Texas Gulf Coast: a regional isotopic study. *In* *Clastic Diagenesis* (eds. McDonald, D.A. and Surdam, R.C.); AAPG Memoir 37, pp. 47-62.
- Larsen, G. and Chilingar, G.V., 1967. Introduction - Diagenesis in Sediments and Rocks. *In* *Diagenesis in Sediments and Sedimentary Rocks* (eds. Larsen, G., and Chilingar, G.V.); Amsterdam, Elsevier, pp. 1-30.
- Leder, F. and Park W.C., 1986. Porosity reduction in sandstone by quartz overgrowth. *AAPG Bulletin*, v. 70, pp. 1713-1728.
- Lee, J.M., 1987. Sedimentology and diagenesis of the Avalon Member of the Mississauga Formation, Hibernia Field, Grand Banks of Newfoundland. MSc. Thesis, Unpubl., University of Calgary, 132 p.
- Leeder, M.R., 1986. *Sedimentology Process and Product*. George Allen and Unwin. London, 344p.
- Lewis, 1984. *Practical Sedimentology*. Stroudsburg Pennsylv., Hutchison Ross Publ. Co., 229p.
- Lindholm, R., 1987. *A Practical Approach to Sedimentology*. Allen and Unwin, 276p.
- Lohmann, K.C., 1983. Unravelling the diagenetic history of carbonate reservoirs: integration of petrographic and geochemical techniques. *In* *A Short Course: New Ideas and Methods for Exploration for Carbonate Reservoirs*. Dallas Geological Society, pp. VI-41.

Lorens, R.B., 1981. Sr, Cd, Mn, And Co distribution coefficients in calcite as a function of calcite precipitation rate. *Geochim. Cosmochim. Acta*, v. 45, pp. 553-561.

Lundegard, P.D., 1989. Temporal reconstruction of sandstone diagenetic histories. *Mineralogical Association of Canada Short Course*, v. 15. Burial Diagenesis, pp. 161-200.

Majiid, A.H., and Veizer, J., 1986. Deposition and chemical diagenesis of Tertiary carbonates, Kirkuk Field, Iraq. *AAPG Bulletin*, v. 70, pp. 898-913.

McKenzie, R.M., 1980. The Hibernia structure: prepared by the frontier group of Mobil Oil Canada Ltd., presented to the Canadian Society of Exploration Geophysicists luncheon meeting on December 9, 1980 in Calgary Alberta; Reported in *Oilweek*, December 15, 1980, pp. 59.

McKenzie, R.M., 1981. Hibernia...a classic structure. *Oil and Gas Journal*, September 21, 1981, pp. 240-246.

McLimans, R.K. and Videtich, P.E., 1989. Diagenesis and burial history of great oolite limestone, southern England. *AAPG Bulletin*, v. 73, pp. 1195-1205.

McMillan, N.J., 1982. Canada's east coast: the new super petroleum province. *Journal of Canadian Petroleum Technology*, v. 21, pp. 95-109.

Meneley, R.A., 1986. Oil and gas fields in the east coast and Arctic basins of Canada. *In* *Future Petroleum Provinces of the World* (ed. Halbouty, M.T.); AAPG Memoir 40, pp. 143-176.

Meyers, J.W., 1989. Trace element and isotope geochemistry of zoned calcite cements, Lake Valley Formation (Mississippian, New Mexico): insights from water-rock interaction modelling.

Mucci, A., and Morse, J.W., 1983. The incorporation of Mg^{2+} and Sr^{2+} into calcite overgrowths: influence of growth rate and solution composition. *Geochim. Cosmochim. Acta*, v. 47, pp. 213-233.

Mucci, A., 1986. Growth kinetics and composition of magnesian calcite overgrowths precipitated from seawater: quantitative influence of orthophosphate ions. *Geochim. Cosmochim. Acta*, v. 50, pp. 2255-2265.

Mucci, A., 1987. Influence of temperature on composition of magnesian calcite overgrowths precipitated from seawater. *Geochim. Cosmochim. Acta*, v. 51, pp. 1977-1984.

Nelson, W.A. and Read, J.F., 1990. Cementation and dolomitization, Mississippian aquifer. *Journal of Sedimentary Petrology*, v. 60, pp. 379-396.

Nentwich, F.W., 1980. Sedimentology and stratigraphy of the Reindeer Formation (Early Tertiary) in the subsurface, Mackenzie Delta-Beaufort Sea Area, Northwest Territories. MSc. Thesis, Unpubl., Carleton University, Ottawa. 125p.

Nentwich, F.W., and Yole, R.W., 1991. Polished thin section preparation of fine grained siliclastic rocks. *Journal of Sedimentary Petrology*, v. 61, pp. 624-626.

Oilweek, 1987. A week of billion dollar decisions. Oilweek, March 16, 1987.

Pettijohn, F., Potter, P. and Siever, R., 1987. Sand and Sandstones. New York, Springer-Verlag, 553p.

Pingitore, N.E. and Eastman, M.P., 1986. The coprecipitation of Sr^{2+} with calcite at 25 C and 1 atm. *Geochim. Cosmochim. Acta*, v. 50, pp. 2195-2203.

Pitman, J.K., Francyk, K.J. and Anders, D.E., 1987. Marine and nonmarine gas-bearing rocks in Upper Cretaceous Blackhawk and Neslem Formations, Eastern Uinta Basin, Utah: Sedimentology, Diagenesis and Source Rock Potential. *AAPG Bulletin*, v. 71, pp. 76-94.

Powell, T.G., 1985. Paleogeographic implications for the distribution of Upper Jurassic source beds, offshore eastern Canada. *Bulletin of Canadian Petroleum Geologists*, v. 33, pp. 116-119.

Powers, M.C., 1953. A new roundness scale for sedimentary particles. *Journal of Sedimentary Petrology*, v. 23, pp. 117-119.

Purcell, L.P., Umpleby, D.C. and Wade, J.A., 1980. Regional geology and hydrocarbon occurrence off the east coast of Canada. *In* Facts and Principles of World Petroleum Occurrence. Canadian Society of Petroleum Geologists, Memoir 6, pp. 551-553.

Rashid, M.A., Purcell, L.P. and Hardy, I.A., 1980. Source rock potential for oil and gas of the east Newfoundland and Labrador shelf areas. *In* Facts and Principles of World Petroleum Occurrence (ed. Miall, A.D.); Canadian Society of Petroleum Geologists, Memoir 6, pp. 589-608.

Ramirez-Muno, J., 1968. Atomic Absorption Spectroscopy and Analysis of Atomic Absorption Photometry. New York, Elsevier Publ. Co., 456p.

Ranganathan, V. and Tye, R.S., 1986. Petrography, diagenesis and facies control on porosity in Shannon Sandstone, Hartzog Drew Field, Wyoming, *AAPG Bulletin*, v. 70, pp. 56-69.

Scherer, M., 1987. Parameters influencing porosity in sandstones: a model for secondary porosity prediction. *AAPG Bulletin*, v. 71, pp. 485-491.

Schmidt, V. and MacDonald, D.A., 1979a. The role of secondary porosity in the course of sandstone diagenesis. In Aspects of Diagenesis (eds. Scholle, P.A. and Schluger, P.R.); SEPM Spec. Publ., 26, pp. 175-209.

Schmidt, V. and MacDonald, D.A., 1979b. Texture and recognition of secondary porosity development on sandstones. In Aspects of Diagenesis (eds. Scholle, P.A. and Schluger, P.R.); SEPM Spec. Publ., 26, pp. 209-225.

Schmoker, J.W., and Highley, D.K., 1991. Porosity of the Lower Cretaceous J Sandstone, Denver Basin, Colorado. *Journal of Sedimentary Petrology*, v. 61, pp. 909-920.

Sclater, J.G. and Christie, P.A.F., 1980. Continental stretching: an explanation of the post-mid-Cretaceous subsidence of the central North Sea basin. *Journal of Geophysical Research*, v. 85, pp. 3711-3739.

Shaunmugam, G., 1985. Significance of secondary porosity in interpreting sandstone composition. *AAPG Bulletin*, v. 69, pp. 378-384.

Sherwin, D.F., 1973. Scotian Shelf and Grand Banks. In The Future Petroleum Provinces of Canada (ed. McCrosan, R.G.); Canadian Society of Petroleum Geologists, Memoir 1, pp. 519-559.

Seibert R.M., Moncure, G.K., and Lahanm, R.R., 1984. A Theory of framework grain dissolution in sandstones. In Clastic Diagenesis (eds. McDonald, D.A., and Surdam, R.C.); AAPG Memoir 37, pp. 163-175.

Sinclair, I.K., 1988. Evolution of Mesozoic-Cenozoic sedimentary basins in the Grand Banks area and Comparison Falvey's (1974) rift model. *Bulletin of Canadian Petroleum Geology*, v. 36, pp. 255-273.

Srivastava, S.P., 1978. Evolution of the Labrador Sea and its bearing on the evolution of the North Atlantic. *Geophys. Journ. Royal Astron. Soc.*, v. 52, pp. 313-357.

Surdam, R.C., Boeses, S.W., and Crossey, L.J., 1984. The chemistry of secondary porosity. In Clastic Diagenesis (eds. McDonald D.A., and Surdam, R.C.); AAPG Memoir 37, pp. 127-151.

Surdam R.C., Croffey, L.J., Hagen, E.S., and Heasler, H.P., 1989. Organic-inorganic interactions with sandstone diagenesis. *AAPG Bulletin*, v. 73, pp. 1-23.

Surdam R.C. and Boles, J.R., 1979. Diagenesis of volcanic sandstones. In Aspects of Diagenesis (eds. Scholle, P.A. and Schluger, P.R.). SEPM Spec. Publ. 26, pp. 227-242.

Swift, J.H., and Williams, J.A., 1980. Petroleum source rocks, Grand Banks area. In Facts and Principles of World Petroleum Occurrence (ed. Miall, A.D.); Canadian Society of Petroleum Geologists, Memoir 6, pp. 567-588.

Tankard, A.J., and Welsink, H.J., 1987. Extensional tectonics and stratigraphy of Hibernia oil field, Grand Banks, Newfoundland. AAPG Bulletin, v. 71, pp. 1210-1232.

Tieh, T.T., Berg, R.R., Popp, R.K., Brasher, J.E., and Pike, J.D., 1986. Deposition and diagenesis of Upper Miocene Arkoses, Yowlumme and Rio Viejo Fields, Kern County California. AAPG Bulletin, v. 70, pp. 953-969.

Veizer, J., 1978. Secular variations in composition of carbonate rocks, II. Fe, Mn, Ca, Mg, Si and minor constituents. Precambrian Research, v. 6, pp. 381-413.

Veizer, J., 1983. Trace elements and isotopes in sedimentary carbonates. In Carbonates: Mineralogy and Chemistry (ed. Reeder, R.J.); Mineral. Soc. Amer., Reviews in Mineralogy. v. 11, pp. 265-299.

Williams, L.A. and Crerar, D.A., 1977. Authigenic clays in sandstones: recognition and influence on reservoir properties and paleoenvironmental analysis. Journal of Sedimentary Petrology, v. 47, pp. 3-31.

Woods, J.R. and Hewett, T.A., 1984. Reservoir Diagenesis and convective fluid flow. In Clastic Diagenesis (eds. McDonald, D.A. and Duram, R.C.). AAPG Memoir 37, pp. 99-110.

Wolf, K.H., and Chillingarian, G.V., 1976. Diagenesis of sandstones and compaction. In Compaction of coarse-grained sediments, II: (eds. Chillingarian, G.V. and Wolf, K.H.); Elsevier, Amsterdam, p. 69-444.

Zinkernagel, v., 1978. Cathodoluminescence of quartz and in application to sandstone petrology. In Contributions to Sedimentology, v. 8, (eds. Fuchtbauer, B., Lisrtzyn, A.P., Milliman, J.D. and Seibold, E.).

Appendix I: Sample Index

Abbreviations

TS: thin sections
D: duplicate thin sections
FR: samples impregnated with blue-dyed epoxy (Nentwich and Yole, 1991)
PC: mineralogical point counts
Q: qualitative estimate
Q': no measurements
SZ: grain size analysis
Ca: carbonate staining
Fp: feldspar staining
XRD: x-ray diffraction
AS: atomic absorption spectroscopy
SE: scanning electron microscopy
IS: stable carbon and oxygen isotopes
MP: microprobe analysis
CL: cathodoluminescence

Appendix 1: Core Samples (... continued)

Sample	Depth (m)	TS	D	FR	PC	SZ	Ca	fp	X	AS	SE	IS	MP	CL
TN-K-07-8	3355.05	X	X	X	X	X							X	X
TN-K-07-9	3358.50	X	X	X	X	X				X	X		X	X
TN-K-07-10	3365.01	X	X	X	X	X				X				X
TN-K-07-11	3366.30	X	X	X	X	X				X				X
TN-K-07-12	3373.00	X	X	X	X	X								X
Date: 89 08 (Terra Nova)														
Collected: B. Welsford														
TN-E-79-1-1	3223.75	X	X	X	X	Q ¹								
TN-E-79-1-2	3224.70	X	X	X	X	Q ¹								
TN-E-79-1-3	3229.70	X	X	X	X	Q ¹								
TN-E-79-1-4	3232.65	X	X	X	X	Q ¹								
TN-E-79-2-5	3263.90	X	X	X	X	Q ¹								
TN-E-79-2-6	3269.70	X	X	X	X	Q ¹								
TN-E-79-2-7	3273.51	X	X	X	X	Q ¹								
TN-E-79-3-9	3277.30	X	X	X	X	Q ¹								
TN-E-79-3-10	3280.92	X	X	X	X	Q ¹								
TN-E-79-3-11	3285.45	X	X	X	X	Q ¹								
TN-E-79-3-12	3292.58	X	X	X	X	Q ¹								
TN-E-79-4-13	3296.53	X	X	X	X	Q ¹								
TN-E-79-4-14	3298.00	X	X	X	X	Q ¹								
TN-E-79-4-15	3308.75	X	X	X	X	Q ¹								
TN-E-79-5-16	3312.35	X	X	X	X	Q ¹								
TN-E-79-5-16	3321.80	X	X	X	X	Q ¹								
TN-E-79-5-17	3332.53	X	X	X	X	Q ¹								
TN-E-79-6-18	3336.10	X	X	X	X	Q ¹								
Date: 89 08 (Huskey-Bow Valley Bonne Bay)														
Collected: R.V. Yole														
HBV-BB-C-73-1-1	4123.75	X	X	X	X	Q ¹								
HBV-BB-C-73-1-2	4129.60	X	X	X	X	Q ¹								
Date: 89 08 (Huskey Bow Valley Fortune)														
Collected: R.V. Yole														
HBV-FTN-G-57-3-1	4025.80	X	X	X	X									
HBV-FTN-G-57-3-2	4035.30	X	X	X	X									
HBV-FTN-G-57-4-3	4592.75	X	X	X	X									
HBV-FTN-G-57-4-4	4598.50	X	X	X	X									
HBV-FTN-G-57-5-5	4721.30	X	X	X	X									
HBV-FTN-G-57-5-6	4724.00	X	X	X	X									

Sample	Depth (m)	TS	D	FR	PC	SZ	Ca	fp	X	AS	SE	IS	MP	CL
TN-C-09-8-20	3478.36	X	X	X	X									
TN-C-09-8-21	3484.30	X	X	X	X	Q ¹								
TN-C-09-8-22	3484.20	X	X	X	X	Q ¹								
TN-C-09-8-23	3484.52	X	X	X	X	Q ¹								
Date: Summer 1987 (Whiterose)														
Collected: R.V. Yole														
WR-N-22-2-1	3566.27	X	N	X	X	Q ¹								
WR-N-22-2-2	3568.87	X	N			Q ¹				X				X
WR-N-22-3-1	3570.20	X	N			Q ¹								X
WR-N-22-3-2	3572.70	X	N	X	Q ¹				X			X	X	X
Date: Summer 1987 (Whiterose)														
Collected: R.V. Yole														
WR-N-22-1	3378.80	X			X	X			X					X
WR-N-22-2	3392.50	X			X	X			X					X
WR-N-22-3	3565.40	X			X	X			X			X	X	X
WR-N-22-4	3566.27	X			X	X			X			X	X	X
WR-N-22-5	3569.22	X			X	X			X			X	X	X
WR-N-22-6	3573.00	X			X	X			X			X	X	X
WR-N-22-7	3574.10	X			Q	Q								
Date: 87 05 20 (West Ben Mevis)														
Collected: R.V. Yole														
WBN-B-75-1	2088.10	X			X	X			X					
WBN-B-75-2	2094.20	X			X	X			X					
WBN-B-75-3	4481.15	X			X	X			X					X
WBN-B-75-4	4494.40	X			X	Q			X					X
WBN-B-75-5	2062.60	X			X	X			X					X
WBN-B-75-6	2063.50	X			Q	Q								
Date: Summer 1987 (Whiterose)														
Collected: R.V. Yole														
WR-J-49-1	3916.10	X			X	X			X					
WR-J-49-2	3920.50	X			X	X			X					
Date: Summer 1987 (South Mara)														
Collected: R.V. Yole														
SM-C-13-1	4392.52	X			X	X			X					X
SM-C-13-2	4400.50	X			X	X			X					X
SM-C-13-3	4586.84	X			X	X			X					X
SM-C-13-4	4588.29	X			X	X			X					X

Appendix I: Core Samples (... continued)

Sample	Depth (m)	TS	D	FR	PC	SZ	Ca	fp	X	AS	SE	IS	MP	CL
Date: 87 12 11 (Terra Nova)														
Collected: D.M. Brown														
TN-K-08-3-1	3341.75	X		X										X
TN-K-08-4-1	3345.20	X		X										X
TN-K-08-6-2	3347.00	X		X										
Date: 87 12 11														
Collected: D.M. Brown														
TN-K-18-1-1	3204.42	X	X	X	X	X	X	X	X					X
TN-K-18-2-1	3218.37	X	X	X	X	X								X
TN-K-18-2-2	3221.90	X	X	X	X	X	X	X	X					X
TN-K-18-3-1	3235.65	X	X	X	X	X								X
TN-K-18-3-2	3238.49	X	X	X	X	Q								X
TN-K-18-4-1	3248.96	X	X	X	X	X								X
TN-K-18-4-2	3254.60	X	X	X	X	X								X
TN-K-18-6-1	3262.25	X	X	X	X	X								X
TN-K-18-6-2	3262.60	X	X	X	X	X	X	X	X					X
TN-K-18-7-1	3266.00	X	X	X	X	X								X
TN-K-18-7-2	3268.72	X	X	X	X	X	X	X	X					X
TN-K-18-8-1	3282.74	X	X	X	X	X								X
TN-K-18-9-1	3293.50	X	X	X	Q									X
TN-K-18-9-2	3299.50	X	X	X	X	X								X
TN-K-18-10-1	3305.55	X	X	X	X	X								X
TN-K-18-11-1	3312.92	X	X	X	Q									X
TN-K-18-11-2	3319.93	X	X	X	Q	X								X

Sample	Depth (m)	TS	D	FR	PC	SZ	Ca	fp	X	AS	SE	IS	MP	CL
Date: 87 12 02														
Collected: D.M. Brown														
SM-C-13-5-1	4395.30	X		X	X	X	X							
SM-C-13-5-2	4396.46	X		X	X	X	X							
SM-C-13-6-1	4582.90	X		X	X	X	X							X
SM-C-13-6-2	4585.33	X		X	X	X	X							X
Date: Summer 1987 (Terra Nova)														
Collected: R.W. Yole														
TN-K-18-1	3204.32	X			X			X						X
TN-K-18-2	3242.75	X			X		X							X
TN-K-18-3	3256.50	X			Q			X						X
TN-K-18-4	3262.40	X			Q			X						X
TN-K-18-5	3264.30	X			Q			X						X
TN-K-18-6	3265.60	X			Q			X						X
TN-K-18-7	3270.30	X			Q			X						X
TN-K-18-8	3283.60	X			Q			X						X
TN-K-18-9	3284.85	X			Q			X						X
TN-K-18-10	3295.20	X			Q			X						X
TN-K-18-11	3307.00	X			Q			X						X
TN-K-18-12	3322.75	X			Q			X						X

Probable errors in point counts

Appendix III: Representative XRD Spectra

END

17-12-93

FIN