Diagenesis Of The GooseTickle Group,
Western Newfoundland

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Summary

This report discusses the reservoir potential of the Ordovician Goose Tickle Group of western

Newfoundland, its relationship to potential source rocks, and to other possible siliciclastic reservoirs in the area.

The Goose Tickle Group contains two main siliciclastic units, the American Tickle Formation and the Mainland Formation. These two units are at least partly lateral time equivalents, and were deposited in the foreland basin which evolved during the mid- Ordovician destruction of the passive margin of the Iapetus Ocean. In terms of a real extent the Goose Tickle Group is dominated by the American Tickle Formation, a unit of variable thickness (150 - ?700 m) which consists mainly of argillite with minor sandstone. Sand content in the American Tickle Formation is low, with only two localities showing a net sand content greater than 50% and all others showing net sand contents of 20% or less. The mainland Formation, consisting mainly of sandstones and siltstones (sand content >80%), is restricted to the west coast of the Port au Port Peninsula. The Mainland Formation at its type section has a minimum thickness of 622 m. The unit is interpreted as having been deposited under oxygenated conditions in the mid-fan area of a submarine fan (or fans) in an oversupplied part of the foreland basin.

As a result of this study, the following conclusions have been reached:

1. Areas of sufficient net sand to suggest possible reservoir potential occur in only two zones of limited extent (the Table Cove/Bellburns, and Mainland areas).

2. Estimates of the offshore extent of the Mainland Formation and the American Tickle Formation are inaccurate because of poor structural control onshore, but regional facies relationships suggest generally sand-poor deposits are to be expected offshore.

3. The low visual porosity in both of the identified sand-rich zones suggests that neither has reservoir potential. The main controlling factor is the lack of porosity, which is ultimately controlled by high initial matrix content and poor sorting.

4. The upper part of the mainland Formation contains the most porous rocks, with porosity being generated through the dissolution of chloritised serpentine grains, probably by fluids generated through the maturation of organic matter in associated shales.

5. Extrapolations from more northerly areas at higher diagenetic grade suggest that deeper offshore burial of lithologies observed in the sand-rich zones onshore is unlikely to have produced substantial secondary porosity.

6. The presence of abundant organic rich shale chips as fragments in the mainland and American Tickle Formations suggests that suitable source rocks did exist along the eastern margin of the foreland basin, and regional relationships suggest that the best analogues for these are to be found in the Lower Ordovician shales of the Humber Arm Allochthon. However, the timely relationship of maturation of organic matter in these rocks to the development of reservoirs has not been demonstrated.

Methodology

This study was designed to use the author's previous knowledge of the mainland and American Tickle formations of the Goose Tickle Group, in combination with standard petrographic methods, to investigate the controlling influences on diagenesis and hence reservoir potential of sandstones of the two units. The original proposal called for isopach and other maps to delineate areas of greatest reservoir potential. However, the structural control for the area is so poor, that it is impossible to provide standard maps of this type. Diagrammatic information is, however, provided, which attempts to portray the variation in important parameters over the area of interest to Mobil.

In total about 120 thin sections were examined. 36 representative samples were stained for potassium feldspar and plagioclase feldspar and point counted using the Gazzi-Dickinson method as described in

Ingersoll et al. (1984). Duplicates of 96 thin sections were made using blue epoxy for impregnation. Examination of these showed that megascopic porosity was virtually non-existent. The author then tried (with limited success) various techniques including fluorescent epoxy dyes and pore casting to try to give an indication of microporosity. Supplementary Scanning Electron Microscope (SEM) investigations of gold coated stubs, as well as backscattered examination of carbon coated thin sections were undertaken. Approximately 40 polished thin sections were included in the study, of which 15 were carbon coated. Polished sections were examined to clarify diagenetic features, utilising light, cathode luminescence and fluorescence microscopy.

Requests from Mobil suggesting modifications to the original proposal had called for studies using vitrinite reflectance and analyses for Total organic Carbon (TOC) to evaluate source potential of the American Tickle Formation. However, the author was also constrained by the terms of the agreement to work with samples already collected for previous projects. Previous field work had concentrated on the collection of sandstone samples from the relevant units, and few samples of potential source rocks had been collected. Pursuit of TOC analyses for sandstones was considered impractical, and the age of the rocks makes them unsuitable for vitrinite reflectance analysis.

The original proposal had postulated that shale chips within the mainland and American Tickle sandstones may provide a possible clue to source rocks. Preliminary investigations suggested that it would be unfeasible to try to extract the chips and determine their organic content, and instead a combination of transmitted and fluorescent light studies were utilised to examine the shale chips and evaluate their source rock potential.

Detailed report

Introduction and General Stratigraphy

Western Newfoundland represents a remarkably complete record of the development and subsequent destruction of an ancient continental margin. The stratigraphy of western Newfoundland (figure 1) is summarised briefly below (see figure 2).

Crystalline basement of Grenvillian (1100 my) age is overlain by rift related clastic and carbonate rocks of the Labrador Group (Precambrian - Lower Cambrian; Cumming, 1983). These are overlain by carbonates of the Cambrian - Lower Ordovician Port au Port and St. George groups (Chow, 1986; Knight and James, 1987; Williams et al., 1987), which record the development and continued existence of a stable carbonate platform. Unconformities within the St. George Group represent the first stages of the destruction of the carbonate platform, with the formation of a western peripheral bulge marginal to a flexural foreland basin (Jacobi, 1981; Knight et al., 1991). Limestones of the Table Head Group record the final stages of existence of the carbonate platform and its foundering to form the floor of the foreland basin. Siliciclastics of the Goose Tickle Group (commonly referred to in Newfoundland literature as Ordovician flysch) were subsequently deposited in the foreland basin, beginning in the Llanvirn. Foreland basin fill (the Goose Tickle Group) consists of fine grained deposits of the Black Cove Formation which are overlain by coarser grained deposits of the widespread American Tickle Formation and its more restricted equivalent, the mainland Formation. Later deposits include the mixed clastic/carbonate Long Point Group (middle Ordovician), and the Silurian/Devonian Clam Bank Formation, again a mixed carbonate/clastic unit.

Western Newfoundland has been subjected to two main phases of deformation, the Taconic Orogeny (mid-Ordovician) and the Silurian/Devonian Acadian Orogeny. Deformation resulting from the Carboniferous Alleghanian Orogeny is less intense in western Newfoundland than in southern parts of the Appalachians.

The sedimentary sequence described above (usually referred to as the autochthonous or parautochthonous sequence) was overridden during the Taconic and Acadian orogenies (see e.g. Cawood and Williams, 1988; Stockmal and Waldron, 1990, 1991; Waldron and Stockmal, 1991) by complex allochthonous terranes (the Humber Arm and Hare Bay Allochthons) . The allochthonous terranes, in addition to ophiolites and volcanic rocks, contain a sedimentary sequence which consists of a lower siliciclastic group, a middle carbonate group, and an upper siliciclastic group. These allochthonous sediments also reflect a history of margin development and destruction (see figure 3 for a summary of the stratigraphy), but they were deposited farther offshore from the ancient continental margin, and have subsequently been transported cratonward on top of their parautochthonous equivalents.

Although the main targets for oil exploration in western Newfoundland are the platform carbonates, the known occurrence of oil associated with Ordovician flysch in the Humber Arm Allochthon (e.g. Fleming, 1970; Sinclair, 1990) suggests that the reservoir potential of foreland basin sandstones of the Goose Tickle Group is worthy of at least some investigation. Sinclair (1990) did suggest that sandstones in western Newfoundland may provide secondary exploration targets.

This report will discuss the reservoir potential of the Goose Tickle Group, the relationship of the Goose Tickle Group to potential source rocks, and its relationship to other potential reservoirs in western Newfoundland.

The Goose Tickle Group - Previous work

The Goose Tickle Group (figures 4, 5) is Llanvirn in age, but there are some indications that it may extend into the Llandeilo (Tuke, 1966; James and Stevens, 1982), although these are as yet unconfirmed (Quinn, 1952). At the base of the group is the Black Cove Formation, a thin unit of shales and siltstones which was previously referred to the Table Head Group, but which was reassigned to the siliciclastic Goose Tickle Group by Stenzel et al. (1990) and Quinn (in prep.).

Throughout most of western Newfoundland the Black Cove Formation is overlain by silty argillites and sandstones of the American Tickle Formation. On the western shore of the Port au Port Peninsula (Map 1), however, the Black Cove Formation is not present, and instead limestone conglomerates and shales of the Cape Cormorant Formation (uppermost Table Head Group) are overlain by sandstones of the mainland Formation.

Siliciclastics of the Goose Tickle Formation were first given formal designation by Cooper (1937). The first work relating to the sedimentology and tectonic significance of the Goose Tickle was a PhD thesis by Tuke (1966), the stratigraphic aspects of which were summarised by Tuke (1968). Both of these authors concentrated their work in the Pistalet Bay and Hare Bay areas of the Northern Peninsula (Map 4). Stevens (1976), also in a PhD thesis, coined the term Mainland Greywacke Sequence for Ordovician sandstones on the Port au Port Peninsula, but had previously discussed the tectonic significance of this and other Ordovician flysch units in his classic (1970) paper on the tectonic evolution of western Newfoundland.

Subsequent work on Ordovician flysch has mainly involved mapping of equivalent units to those described above, and a proliferation of informal names has resulted (see discussion in Quinn, 1992). Quinn (1991, 1992, in prep.) proposed a resolution of the disorganised stratigraphic nomenclature, which is shown in figure 4, and this stratigraphic scheme was published with permission in preliminary form by Stenzel et al. (1990). Quinn (1992) has recently defended a PhD thesis which represents the only substantial body of work summarising the stratigraphy, sedimentology, provenance and geochemistry of the newly defined Goose Tickle Group as well as the related allochthonous unit, the Lower Head Formation. An uncorrected version of that thesis is presented as an accompaniment to this report.

Virtually no work has been carried out on the hydrocarbon potential of the Goose Tickle Group, but Sinclair (1990) considered the unit a poor potential reservoir, at least in the Port au Port Peninsula area.

Distribution and sedimentology of the Goose Tickle Group

The regional distribution of the Goose Tickle Group is shown in figure S. The following summary of the characteristics of the American Tickle and Mainland Formations is from Quinn (1992).

The American Tickle Formation

The American Tickle Formation is generally considerably deformed, with deformation increasing eastward towards the transported terranes. In many cases American Tickle lithologies form the matrix to melanges at the bases of the allochthons. An accurate thickness, even of the formation stratotype, cannot be obtained, and many previous authors have estimated thicknesses based simply on outcrop width. The top of the formation is almost everywhere marked by the basal thrust of a transported terrane. The variable thicknesses shown in the accompanying maps may be as a result of deformation or they may reflect true depositional differences. it is likely that both factors affect the observed apparent thickness of the unit.

The American Tickle Formation is a unit dominated by silty argillites which are massive or graded and are interbedded with 1-5 cm thick beds of black silty mudstone. Sandstones in the American Tickle Formation are most abundant near the base of the unit. Throughout almost the entire areal extent of the American Tickle Formation, sandstones constitute less than 20% of any given outcrop. The dark silty mudstones which occur within the American Tickle Formation consist of thin (1 - 3 cm thick) thinly laminated organic rich black bands which contain abundant scattered coarse silt grains and framboidal pyrite grains. These are interbedded with the dominant lithology, an impermeable silty argillite, and rarely reach 10% of the total outcrop at any locality. The only samples collected by the author from these organic rich layers were from Pistolet Bay (map 4) and in these samples the organic matter is completely black and non-fluorescent. Sandstones in the American Tickle Formation are fine to coarse grained, medium to thick-bedded, commonly amalgamated, and typically show Tac or Tace Bouma (1962) sequences. At only two localities, Bellburns and Table Cove, are there significant sandstone accumulations (Map 3). Gross sand thickness at Bellburns is about 127 m and at Table Cove it is 59 m. These are minimum values as the tops of these sections are not exposed. Net sand thickness at Bellburns is approximately 70 m and at Table Cove is 45 m. Approximately 50% of the sandstones at each of these localities are coarse grained.

Sandstone beds at the Bellburns and Table Cove localities reach up to 1 m in thickness, and are cross-bedded. The cross- bedding is likely present because of the abundant coarse sediment supply which has resulted in deposition of a modified Bouma sequence as described by Allen (1970). Thus, reworking and removal of fines, which might have increased initial porosity and permeability, is not indicated for these cross-bedded sandstones.

The association of facies described above was interpreted by Quinn (1992) as representing deposition in an 'outer fan' setting within the foreland basin proper. The term 'fan' should be used with caution, since paleocurrents in the American Tickle Formation are predominantly directed towards the southwest, and the geometry of a fan cannot be documented. The uniform paleocurrent directions indicate oversupply of sediment to the basin and confinement of flows by the basin geometry. The lack of disruption of laminations in the finer grained parts of the American Tickle, in combination with the lack of trace fossils, and abundant diagenetic pyrite, suggests that the formation was deposited under anoxic and probably reducing conditions.

Throughout its entire extent in western Newfoundland, the American Tickle Formation includes variable thicknesses of limestone conglomerates which have been assigned to the Daniel's Harbour Member (Stenzel et al., 1990). In the Northern Peninsula and the northeast Port au Port Peninsula, polymictic conglomerates of the Howe Harbour Member (Quinn, 1992) occur within the American Tickle Formation. These conglomerates are dominated by black and green shale chips and are clearly derived from the Hare Bay and Humber Arm Allochthons. They occur in a coarsening upward sequence as obvious precursors to Middle Ordovician emplacement of at least the sedimentary parts of the allochthons.

The mainland Formation

The sand-rich mainland Formation is restricted to the west coast of the Port au Port Peninsula. The Mainland Formation at its type section is a minimum of 622 m thick (Three Rock Cove, see Map 1), with neither base nor top exposed. At the type section, 82% of the section consists of sandstones. of the sandstones, an estimated 25% are coarse grained.

The Mainland Formation consists predominantly of fine- to medium-grained sheet-like classical turbidites, with lesser amounts of very thick-bedded medium- to coarse-grained massive sandstones, with cross-bedded sandstones becoming more prominent near the top of the section. These cross-bedded sandstones have scoured bases, and may be associated with reworking of sand grains, hence they may have had an originally higher porosity and permeability than other facies of the mainland Formation.

The Mainland Formation is interpreted to have been deposited in the mid-fan area of a submarine fan, which, however, was again confined by the basin geometry, resulting in predominantly south directed paleocurrents in the type section. Where the mainland Formation overlies the Cape Cormorant Formation, however, paleocurrents are directed to the northwest, which may be as a result of lobe switching, which is a common occurrence among turbidites deposited in topographically complex areas.

Estimation of thickness is a problematic aspect of the Mainland Formation. The thickness quoted above is a minimum value since neither the top nor the base of the type section are exposed. A short section (15 m) of mainland sandstone (thin - medium-bedded turbidites) is seen in contact with the Cape Cormorant Formation, and this is commonly the only example of mainland lithologies seen on standard field trips in the area. A third section is exposed along the coast in the village of Mainland, but this section is disrupted and again neither base nor top are exposed.

The contact between the Mainland Formation and the underlying Cape Cormorant Formation appears conformable, but it has also been interpreted by several visitors to the outcrop as a bedding- parallel fault, which would presumably place younger material (Mainland) over older (Cape Cormorant).
Previous workers (e.g. Schillereff and Williams, 1979) have identified a section at Low Point (figure 6, and map 1) as the youngest exposed example of Mainland lithologies. The approximately 60 m thick section at Low Point is separated from the Three Rock Cove and Mainland sections by faulted and sheared shales containing 10 to 20 m thick packages of sandstone which are typically medium- to thick-bedded, coarse grained, and show considerable evidence of soft sediment deformation.

Evidence which appeared to indicate that Low Point represents the highest exposed level in the Mainland formation (Schillereff and Williams, 1979) included:

1. The continuity of outcrop between the section, from Crow Head to Low Point;

2. The presence at Low Point of graptolites of Llandeilo age (James and Stevens, 1982), which is younger than the Llanvirn age assigned to the rest of the Mainland Formation;

3. The broad similarity of lithologies at the Low Point with other parts of the Mainland Formation;

4. The tendency of sandstones at Low Point to be cross-bedded, calcareous, and more quartzose than the rest of the Mainland Formation - which, combined with 3, was interpreted to reflect a transition between the Mainland Formation and Long Point Group;

5. The similarity of strike and dip between the Low Point section and the offshore Cow Rocks (now included with the Long Point Group) (see figure 6), suggesting a stratigraphic contact between the two units (Schillereff and Williams, 1979; H. Williams, pers. comm., 1992).

This hypothesis of stratigraphic continuity between the mainland Formation and the Long Point Group would imply a substantial thickness (>1.5 km) for the mainland Formation. Problems with this hypothesis are as follows:

1. The author has documented several bedding parallel faults within the Mainland Formation which make suspect any assumptions of stratigraphic continuity between the Mainland and Three Rock Cove sections and Low Point, and between Low Point and the Cow Rocks.

2. S.H. Williams (pers. comm., 1991) has pointed out that the collection of fauna from the Low Point section has never been figured in a publication, and he considers the Llandeilo age to be unsubstantiated.

3. Recent work (Stockmal and Waldron, 1990, Waldron and Stockmal, 1991) based on information from offshore seismic lines has indicated that the platform and foreland basin sediments on the Port au Port Peninsula have been structurally incorporated into a triangle zone, and that the Long Point Group has in fact been thrust over the mainland Formation, with the thrusted contact being

located somewhere between Low Point and the Cow Rocks.

Three possible interpretations for the rocks at Low Point are possible with the currently available information.

1. Faults at the base of the Low Point section place younger over older material, and represent smaller faults in the same sense as the main triangle zone fault. This could be the case whether the Low Point section is Llanvirn or Llandeilo.

2. The Low Point sediments may represent an axial succession of the same age as the rest of the Mainland Formation, which has been faulted against more marginal deposits.

3. The Low Point section may represent upper Mainland rocks whose stratigraphic position relative to the main sections is intact, and faults at the base of the Low Point section and within the type section are minor. This again could be the case whether the Low Point section is Llanvirn or Llandeilo.

In light of these complexities, it is impossible to obtain an accurate estimate for the thickness of the mainland Formation. This discussion is more than academic, because, as will be detailed below, the most significant porosity in the Mainland Formation occurs within the sandstone packages in shales below the Low Point section, and in the Low Point section itself. It is clear that this study cannot resolve these questions, and that it is crucial to recollect the fauna at the Low Point section. This the author has done, but the samples have not yet been submitted for identification.

On the basis of gradual changes visible near the top of the type section, the author believes that the Low Point section is younger than the type section, and that the increase in shale content from the type section to Low Point represents an overall fining upward sequence.

Regional Considerations

The model drawn by Quinn (1992) for the basinal setting for the American Tickle and mainland Formations is as follows (figures 7 and 8). The American Tickle Formation is interpreted to be have been deposited as mainly outer fan deposits in an oversupplied foredeep basin under anoxic conditions.

Quinn (1988) initially interpreted the westerly location of the sand rich zones at Bellburns and Table Cove as an anomalous westward coarsening sequence (assuming that the sandstones were ultimately derived from the orogenic area to the east), but subsequently suggested (Quinn, 1992) that sand/mud ratio variations along the length of the foreland basin occur because there were at least two sediment input points along the American Tickle part of the basin. This was suggested on the basis that a higher sand/mud ratio implies a closer proximity to a sediment input point (Underwood and Bachman, 1982).

The inferred location of sediment input points is shown in figure 7. Please note that the model shown in figure 7 is based on outcrop examination of localities from Bonne Bay northward. South of Bonne Bay, less information is available, and it is possible that an additional sediment input point could have supplied that segment of the basin.

The Howe Harbour Member is interpreted as a coarsening upwards sequence of gravity flow deposits generated by thrusting of pre- existing slope sediments, and like the Daniel's Harbour Member (Stenzel et al., 1990), is a precursor to the arrival of the lower slices of the Humber Arm and Hare Bay allochthons (Quinn, 1991, 1992; see also Corney, 1991).

The sand-rich nature of the mainland Formation indicates the existence of a third sediment input point at the southern end of the same oversupplied basin, but this formation was deposited under well-oxygenated conditions in a tectonically and topographically complex area characterised by lobe switching and reactivation of pre-existing rift-related faults prior to the emplacement of the Humber Arm Allochthon. The mainland Formation in its type area was somewhat removed from the leading edge of the Humber Arm Allochthon, however, it shows abundant evidence of rapid deposition and active tectonism.

The lack of megaturbidites in the foreland basin system suggests that the eastern side of the basin was steep sided compared to the foreland basin in Quebec (see Hiscott et al. 1986 for a summary of foreland basin characteristics in Quebec) , and the fact that both formations of the Goose Tickle Group seem to fine upward is attributed to a gradually rising sea level during the Llanvirn (Fortey, 1984).

For comparative purposes, it is worth noting that Quinn (1992) has interpreted allochthonous flysch of the Lower Head Formation as a series of small submarine fans which were probably deposited in a small trench slope basin or basins. Facies relationships in these deposits indicate that the eastern shelf of the basin(s) was very narrow, suggesting supply by fan deltas on steep slopes, and the clast content of conglomerates suggests that contemporaneous uplift and cannibalisation of pre-existing slope/rise sediments was taking place to the east.

It is important to note that field relationships in all three Ordovician flysch units in western Newfoundland do not support the notion of a flysch shed directly from and obtaining its character wholly from the advancing Humber Arm and Hare Bay allochthons.

<u>Known vs. inferred distribution of sand rich material</u>
Since thickness estimates for both the Mainland and American Tickle formations are approximate only, and insufficient control points are available, accurate isopach maps cannot be constructed. Maps 1A, 2A, 3A and 4A show localities where the thickness of the units have been measured or estimated. Since gross sand thickness and net sand thickness are dependent on known stratigraphic thickness, the inability to produce isopach maps affects the production of these maps also. Instead, maps 1A, 2A, 3A, and 4A show localities where estimates have been made of the percentage sand content, and these can be related to thickness estimates in order to visualise the amount of sand present.

The best way of predicting the distribution of American Tickle and mainland sands offshore is to make use of the model for the foreland basin constructed in Quinn (1992) and summarised in section 2.4. Bradley (1989) has suggested that the axial region of the foreland basin was no more than 15 km wide, and the restricted paleocurrent directions measured by the author provide additional support for a narrow confining geometry. Based on the most westerly outcrops now observed, all of which have a depositional character suggesting deposition in axial regions, the basin axis is unlikely to have extended farther west than the dotted line shown on figure 9. Eastward thrusting of the unit is likely to have complicated matters, but figure 25 of Sinclair (1990) supports the suggestion that the Goose Tickle Group may not extend further than a few kilometers offshore. The only locality where the amount of shortening has been quantified (approximately 30 km) is the Port au Port Peninsula (Waldron and Stockmal, 1991). It is as yet unclear whether platformal rocks in other parts of western Newfoundland have undergone significant westward transportation, and there are several major fault structures (e.g. the Ten Mile Thrust) which may also have affected offshore equivalents of the Goose Tickle Group (Grenier and Cawood, 1988; Grenier, 1990).

The most sand-rich parts of the American Tickle Formation (Bellburns/Table Cove) occur in westerly coastal areas, and in these areas the beds are dipping and facing west (offshore).

Regionally, the American Tickle Formation appears to be fining upwards, and thus, if the regional dip remains broadly unchanged, the offshore (younger) portion of the unit is predicted to be sand- poor.

Expected facies variations in foreland basin fill include wedging out of sand bodies in the direction of the foreland (e.g. Ricci-Lucchi, 1986). This type of relationship has not been identified within the American Tickle Formation, and may be unlikely, given the narrow configuration of the basin. However, it still would suggest that, even if the regional dip shallows offshore, equivalents of the American Tickle Formation are likely to be finer grained and more sand-poor than lithologies visible onshore.

The offshore distribution of the Mainland Formation is not simple to predict, since it occurs in an area of considerable structural complexity and it is not of such wide regional extent as the American Tickle Formation (see section 2.3.2). However, like the American Tickle Formation, the Mainland Formation also appears to fine upward, and this, combined with the westward fining to be expected from facies relationships, suggests that the westward offshore portion of the unit is most likely to be of finer grain size than that exposed onshore.

Paleocurrent directions from the type section of the Mainland Formation are towards the southwest, which might imply that sand rich material could extend several 10's of kilometres offshore in a southwesterly direction. However, paleocurrent directions near the mainland/Cape Cormorant contact are to the northwest, suggesting that more than one lobe characterised this system, or that ponding took place against topographic features in this complex area. The prediction that sand rich material may extend southwest of the current outcrop area is thus tentative at best.

General Petrography

Petrographic investigations show that the mainland and American Tickle formations are similar. Sandstones from both formations are moderately to poorly sorted, and range in grain size from fine to very coarse. Rounding varies from well rounded to subangular depending on grain type. most of the samples can be classified as lithic wackes or feldspathic lithic wackes (using the classification of Dott, 1964).

Quartz is dominantly monocrystalline, with slightly undulose extinction, and variable rounding. Inclusions other than vacuoles are rare, but a small percentage of quartz grains contain needle- like inclusions, probably of rutile.

Feldspars include albite twinned plagioclase, untwinned plagioclase, and microcline. Plagioclase feldspars are generally subangular to subrounded, whereas microcline grains are frequently well-rounded, although angular examples do occur.

Sedimentary rock fragments (laminated and unlaminated shale chips with lesser amounts of siltstone) dominate the rock fragment population, with other fragments including siliceous, intermediate and mafic volcanics, siliceous plutonics, micritic limestone, ooids, and phyllite. Rock fragments are predominantly subrounded. An unusual feature of the framework population is the abundance of large (>mean grain size) grains of phyllosilicate, many of which were optically identified as serpentine on the basis of their common mesh-like texture and their association with chromite. These grains were subsequently demonstrated through electron microprobe and SEM analyses to be chlorite.

Heavy minerals include chromite, zircon, monazite, biotite and muscovite.

The petrographic similarity between the Mainland Formation (mean of 21 samples) and the American Tickle Formation is shown in Tables 2, 3 and 4 (see also table 1 for explanations of abbreviations). Two tables for the American Tickle Formation are shown, one from the Table Cove/Bellburns area (mean of 10 samples), and one from the Northern Peninsula (mean of 5 samples). The latter is outside Mobil's area of interest but is nevertheless instructive, as it is more altered, and may provide a clue as to the likely appearance of mainland and Bellburns/Table Cove sands if they are buried to greater depths offshore. Although modal abundances for the Mainland and Table Cove areas are very similar, samples from the Northern Peninsula show a higher percentage of matrix (much of which is likely secondary) and a lower percentage of phyllosilicate grains. The phyllosilicate grains may have been altered or the may have been supplied through the northernmost sediment input point in lesser abundance. It should be noted that all mean values for modal abundances show high standard deviations, a feature which is attributed to variations among facies, variations within facies (e.g. variations between samples collected from division A of the Bouma sequence, vs. samples collected from division C), and variations in grain supply between different turbidity flow events.

The general petrographic uniformity throughout the entire Goose Tickle group, as demonstrated by examination of tables 2, 3 and 4, suggests mixing of the sediment supply. This may have taken place in an upper trench slope basin or basins prior to transport and deposition into the foreland basin proper, but more detailed statistical studies might allow for distinction of petrographic signatures between samples derived from different sediment input points.

Provenance

Detritus to the Goose Tickle group was supplied by a variety of sources which included:

a. mafic volcanic rocks (extrabasinal)
b. mafic plutonic rocks (extrabasinal)
c. andesitic/rhyolitic volcanic rocks (extrabasinal)
d. felsic plutonic rocks (extrabasinal)
e. cemented quartzofeldspathic sandstones and oolites (extrabasinal)
f. black and green shales (marginal to the basin)
g. low grade metamorphic rocks (extrabasinal)
h. intraformational/intrabasinal sediments

Mafic volcanic and plutonic fragments may have been derived from ophiolites, but there are other non-ophiolitic volcanic rocks present in the Humber Arm and Hare Bay allochthons, some as separate structural slices, others intruding or stratigraphically associated with Cambrian sandstones. Therefore a number of sources could have contributed the mafic volcanic/plutonic component.

Andesitic/rhyolitic volcanic fragments are thought to have been derived from island arcs which were located to the east of the foreland basin. Felsic plutonic rocks may have been derived from the plutonic roots of these arcs.

Laminated and unlaminated (black and green in hand specimen) shale chips, despite their similarity to lithologies currently interbedded with the sandstones, appear in some samples to have undergone a greater degree of diagenetic alteration than the sandstones themselves, and must therefore represent material eroded from the eastern margins of the foreland basin, rather than strictly intraformational fragments.

Ooids and clean quartz cemented sandstones and siltstones may have been derived from shelfal areas fringing the uplifted orogen. Their scarcity suggests that these shelfal areas were not very extensive, and the recycled nature of the sandstones suggests that they were unlikely to have been deposited marginal to the foreland basin, but instead fringed a basin closer to the orogen in which sediment was stored before being supplied to the lower trench slope basins and foreland basin proper.

Intraformational/intrabasinal clasts are interpreted as rip-up clasts from immediately underlying sediments. The most obvious source for ultramafic detritus is an ophiolite, and several papers (e.g. Bradley, 1989; Stockmal and Waldron, 1990) directly relate ultramafic detritus in the sandstones to the emplacement of the Bay of Islands Ophiolite in the Humber Arm Allochthon. However, there is proportionately less mafic volcanic detritus in the sandstones than would be expected from the gradual unroofing of an upright ophiolite (see also Hiscott, 1979). Quinn (1992) has suggested that an alternate source for chromite and serpentine might be serpentine diapirs intruded along early emplacement-related faults.

The provenance of quartz and feldspar is most problematic. The quartz population appears identical-to that found in Cambrian sandstones of the Humber Arm and Hare Bay allochthons which were presumably ultimately derived from Grenville basement. The bulk of the evidence (see Quinn, 1992 for summary of electron microprobe investigation of feldspars) suggests that most single plagioclase and potassium feldspar grains do not originate from a volcanic source, but from a metamorphic or plutonic source, and a number of plagioclase feldspars may have been authigenically altered in a prior sedimentary environment. For the rounded potassium feldspar, it is possible that shelfal areas surrounding unroofed arcs may have generated these recycled grains. It may also be possible that Grenvillian basement or its Cambrian cover may have been exposed east of the mixing basin, to provide a basement signature. However, exposure and direct erosion of Grenvillian basement in close proximity to the foreland basin is not envisaged. Equivalents to the Fleur de Lys Supergroup (metamorphosed passive margin sandstones now located along the eastern edge of the Humber Zone) could conceivably have provided potassium feldspar, but the timing of the peak of metamorphism of the Fleur de Lys Supergroup is not well constrained, and it may not have been metamorphosed and uplifted in time to have provided detritus to Ordovician sandstones. The alteration patterns within the potassium feldspars are complex (see below) and a better understanding of them is required before this problem can be resolved.

It is envisaged that the sources of some of the quartz, plagioclase feldspar, and possibly some potassium feldspar may have been sediments similar to the Cambrian Blow me Down Brook, Summerside, and Maiden Point formations now found in the Humber Arm and Hare Bay Allochthons. All of these formations contain abundant untwinned plagioclase feldspar, and the Blow me Down Brook Formation contains minor potassium feldspar.

Field relationships, the mixing implied by the petrographic uniformity along the basin and the fact that neither the Humber Arm or Hare Bay allochthons contain neither abundant siliceous volcanic or plutonic rocks, nor sediments rich in rounded quartz and potassium feldspar, suggest that the Humber Arm and Hare Bay allochthons in western could not have been the sole providers of detritus to the Ordovician sandstones of the Goose Tickle group.

Diagenesis

Diagenetic features and porosity

Diagenetic features are remarkably similar throughout the Goose Tickle Group. The rocks are moderately to poorly sorted, with moderate to high proportions of matrix. Because of the abundance of shale chips, it is frequently difficult to distinguish between primary matrix, secondary matrix, and pseudomatrix.

Quartz overgrowths are present, forming either incomplete or complete rims around quartz grains. The presence of overgrowths is frequently difficult to ascertain, as clay or dust rims are poorly developed on most quartz grains. Quartz overgrowths rarely constitute more than 1% of the total area of a thin section. Potassium feldspar overgrowths on microcline grains are also present in a few samples, and these again are always present in proportions less than 1%.

Grains are generally closely packed, with a high proportion of grains in contact with each other, but in places grains may be 'floating' in patches of carbonate cement. The amount of ductile deformation of grains is variable, even within a single sample. Virtually no intergranular porosity was observed in any sample, but neither was any evidence of pressure solution observed.

The alteration patterns of feldspars are complex, and again may vary within a single sample. Alteration textures are most clearly visible in potassium feldspar grains, and most commonly appear as patches or cores of albite. The patches may be clear or cloudy, and they may or may not be in optical continuity with the original grain. Twinning lamellae are commonly continuous across the patches. Twinning lamellae are commonly continuous across the patches. Plagioclase feldspars may be sericitised, or partly replaced by calcite. Cathode luminescence microscopy shows that many relatively fresh-looking plagioclase feldspars are non-luminescent, and hence have undergone low temperature alteration (Kastner, 1971).

A patchy pore-filling calcite cement is present in most samples. It is variable in its characteristics, but generally two phases of cementation are evident in cathode-luminescence, a faintly luminescing thin cement which occurs as rims around detrital grains (the faint luminescence of calcite indicates a relatively high Fe/Mn ratio, Hemming et al., 1989), and the main pore-filling cement which consists of brightly luminescing calcite (relatively low Fe/Mn ratio, Hemming et al., 1989). There is no evidence of oil migration having inhibited the precipitation of cement. Isolated dolomite rhombs are common and occur both within shale chips and within the body of the sediment as a whole, where they commonly appear as early phase overgrowths which were in place prior to the precipitation of the main pore filling carbonate cement.

Partial and complete carbonate replacement of framework grains is common, with large detrital phyllosilicates, ?polycrystalline quartz, feldspars and siltstones most commonly replaced. in some samples, notably those from the Table Cove/Bellburns area, serpentine grains are altered to quartz, and have distinctive rims of sparry carbonate. Minor mounts of authigenic chlorite and some illite are visible in the Scanning Electron Microscope and occur on the few available exposed surfaces within the framework.

Porosity

American Tickle sandstones were found to be non-porous (0% porosity) on a macroscopic scale, and to contain very little microporosity, with a poor degree of interconnectedness of the micropores. The mainland Formation is more friable and porous than the American Tickle Formation, however, only a few samples show significant porosity and none show a porosity greater than 10%. Very minor amounts of intergranular porosity occur in a few samples, notably those which contain significant early quartz overgrowths, which may have reduced the effects of compaction in the early stages of diagenesis.

The bulk of the observed porosity is a secondary porosity which has been generated by preferential dissolution of chloritised serpentine grains. Although chloritised serpentine is common throughout both the American Tickle and Mainland Formations, porosity generating dissolution of the serpentine appears to be most common in coarse grained samples from the Mainland Formation. Dissolution of the serpentine appears to have occurred preferentially in the grain cores, and also in small veins, which tend to parallel the grain margins. Another controlling factor in the dissolution is the platy structure of the grains, as enhanced permeability appears to have existed between plates, causing preferential dissolution in certain cases. The pores left by dissolution have not been compacted in any way, and still retain the shape of the original grain.

Thin section and SEM studies indicate that pores generally show a poor degree of interconnectedness, suggesting that even in sandstones with relatively high porosity, permeability is low. In general, Moncure et al. (1984) and Siebert et al. (1984) have found that dissolution of framework grains does not significantly enhance permeability. Attempts by the author to make pore casts also suggest non-interconnectedness of pores, as the pore casts did not hold together when framework grains were dissolved.
In only one sample, from near the top of the mainland Formation, a secondary porosity has been generated through dissolution of calcite cement.

In a qualitative way, the most porous samples are most common at or near the top of the Mainland Formation (Low Point section and related facies). This variation may be facies controlled, as the top of the formation (Low Point section and sandstone packages in deformed shales below) contains abundant coarse-grained, cross- bedded sands which appear less matrix rich than the bulk of the formation. Microporosity occurs along the cleavage planes of detrital flakes of some clay minerals, and within rhomb shaped molds in shale chips which have been incompletely filled with calcite. Fractures are common, but are almost always infilled with calcite.

However bedding parallel 'fracture, porosity exists in the friable parallel laminated facies of the mainland Formation, as layers of poorly cemented shale chips mark some of these horizons. These fractures could potentially significantly increase the permeability in a bedding-parallel direction.

The amount of fluorescent organic material in the American Tickle and Mainland formations is low, and none of the sandstones investigated show appreciable oil staining. Clearly, the singular lack of porosity and implied lack of permeability overall of the Goose Tickle group suggests that the unit as a whole has poor reservoir potential.

Paragenetic sentence

The various diagenetic features will be discussed in the order in which they are inferred to have formed.

Quartz and feldspar overgrowths

Numerous authors (e.g. Girard and Deynoux, 1991; Dutton and Diggs, 1990; Bjorlykke, 1988) have attributed the formation of early quartz cement in the form of overgrowths to the actions of meteoric waters at shallow depths. This is the most likely explanation in the case of the Goose Tickle Group, as pressure solution is clearly not a factor, and quartz cement rims are clearly early features which predate calcite cements.

Dutton and Diggs (1990) and Schmoker and Higley (1991) have suggested that abundant clay matrix will inhibit the precipitation of quartz overgrowths, and significant quartz overgrowth may be considered indicative of a low initial percentage of clay matrix and a high initial permeability. Although quartz overgrowths are ubiquitous in the Goose Tickle Group, they are never abundant, and this suggests that initial permeability of the unit was low, and that a significant proportion of the clay matrix was present at the time of deposition.

Bjorlykke (1988) has suggested that authigenic feldspar is usually an early cement, as it is relatively stable in normal seawater, and noted that it rarely constitutes more than 2% of the total rock volume, an observation consistent with those recorded in this study. The presence of authigenic potassium feldspar as an early grain-rimming cement in some samples is indicative of a relatively high ratio of K+/H+ in the porewaters (Pettijohn and Potter, 1987).

<u>Mechanical compaction</u>

The poor sorting of sandstones, and the high percentage of inequant grains in both the American Tickle and the mainland formations suggests that the initial porosity was probably relatively low, in the range of 20-35% (Fetter, 1988). In both units the lack of porosity is attributable mainly to compaction resulting in grain rearrangement. McBride et al. (1991) suggested that for Paleocene-Eocene sandstones of the Texas Gulf Coast, at all depths, the amount of porosity lost by grain rearrangement is more than twice the amount of porosity lost by either measurable ductile grain deformation or pressure solution. Abundant soft grains (shale chips and chlorite/chloritised serpentine) may have further filled pore spaces through mechanical compaction, and carbonate cement precipitated in remaining pore spaces. McBride et al. (1991) noted a wide variation in the amount of porosity reduction through compaction, which ranged in their samples from 9 to 31%. A wide range in porosity reduction through rearrangement was probably also the case in the Goose Tickle Group, since relative abundances of different framework grains and sorting vary from sample to sample and even within a sample. The importance of grain rearrangement in porosity reduction is further suggested by the variable amounts of deformation of ductile grains, even within a single sample.

<u>Alteration of feldspars</u>

The patchy alteration features in potassium feldspars are similar to some of those described by Milliken (1989). However the lack of association of feldspar alteration with extensive secondary porosity suggests that precipitation kept pace with dissolution, and the mobility of A13+ was low, as is normally the case for aluminium (e.g. Moncure et al., 1984; Surdam et al., 1984; Siebert et al., 1984). According to Aagard et al. (1990) the albitisation of potassium feldspar in clastic reservoirs offshore of Norway took place over a wide temperature range (65 - 120 degrees Celcius). Albitisation of potassium feldspar in the lower part of this temperature range (50 to 70 degrees) usually results in secondary porosity, which occurs because precipitation does not keep pace with dissolution at these temperatures (Aagard et al., 1990).

Since secondary porosity is not observed in potassium feldspars of the Goose Tickle Group, it would appear that albitisation in the mainland and American Tickle formations took place at temperatures greater than 70 degrees, or that secondary pores were subsequently filled with calcite and clay minerals. Conodont colour alteration indices for the mainland area suggest temperatures of <50 to 80 degrees (Nowlan and Barnes, 1987) which would be consistent with those suggested by Aagard et al. (1990). However, the patchy textures most resemble type II albitisation of Saigal et al. (1988) which occurs at temperatures >90 degrees, and hence this problem cannot be considered resolved, until more independent information on temperatures and depths of burial (from palynology and possibly graptolite reflectance') are available.

Aagard et al. (1990) state that albitisation of plagioclase occurs within a relatively narrow temperature range (110 to 150 degrees). This seems high, at least for the Mainland Formation, and may support the suggestion that some of the non-luminescing plagioclase grains were albitised in a prior sedimentary environment.

The replacement of some of the feldspars by calcite suggests that feldspar alteration took place prior to or at the same time as carbonate cementation.

<u>Calcite cement</u>

Several lines of evidence suggest that the main pore-filling carbonate cement is a relatively late feature. Firstly, sufficient permeability must have been required to allow for flow of porewaters through the sediment such that feldspars could have been dissolved and replaced, a situation most likely to have existed prior to the main porefilling episode. Also late cracks which cross-cut framework grains and are not themselves deformed are commonly filled with brightly luminescing calcite.

The range of amounts of carbonate cement may be explained by the variable porosity values which probably existed after compaction. However, estimates of carbonate cement abundance have also been affected by complete replacement of framework grains by calcite, which is not obvious in transmitted light, but which is clearly visible in cathode luminescence.

Aagard et al. (1990) have estimated that calcite cement in sandstones offshore of Norway was formed at temperatures of 60 to 70 degrees celcius, but again, more detailed work is required to be more specific regarding temperatures of formation.

<u>Generation of secondary porosity</u>
The only substantial porosity observed anywhere in either the American Tickle or the mainland Formation was generated through dissolution or partial dissolution of chloritised serpentine grains.

The grains were identified as serpentine primarily on the basis of abundant mesh-like textures, which are characteristic of ultramafic serpentines, and the fact that several grains contain chromite, a mineral which is common only in ultramafic rocks. Electron microprobe analyses have shown that these grains are in fact chlorite.

Serpentine is considered an unusual rock fragment, and hence very little information is available on the behaviour of serpentine as a diagenetic mineral. It is unclear whether alteration of serpentine to chlorite took place within the sandstones, or at the source.

Evidence for diagenetic alteration includes:

1. Electron probe analyses indicate that the grain interiors are commonly richer in magnesium relative to aluminium, and grain exteriors are commonly richer in aluminium relative to magnesium. This might suggest exchange of ions around the margin of an already formed grain.

2. Reconnaissance XRD analyses indicate the presence of a strong 7 angstrom peak unaccompanied by the 14 angstrom peak typical of most chlorites. This suggests that chlorite in the sandstones is dominated by a relatively low temperature semi-stable chlorite.

Evidence for alteration at the source includes:

1. The flaky shapes of the grains as seen in the SEM, which is a feature characteristic of a detrital rather than an authigenic origin.

2. The chemistry of these grains is typical of metamorphic chlorites (see figure 10). 3. According to R.K. Springer (pers. comm. , 1990), the alteration referred to in section 2.8.2.1 (to calcite and quartz) is reminiscent of a typical low temperature metamorphic reaction of serpentine, in which serpentine is altered to quartz and magnesite. In cathode luminescence, these rims are dark, and clearly have a different composition than the main pore-filling calcite. However, SEM work showed that the carbonate rims were composed of simple calcite rather than the expected magnesite.

Clearly, the evidence is contradictory and a number of additional points should be considered:

1. The compositional variation within the chloritised serpentine grains could be a result of diagenetic effects, but it could also reflect an original metamorphic variation in a serpentinite which was controlled by the vein structures which are now preferentially dissolved near grain margins.

2. It is unclear what significance the probe data summarised in figure 10 might have, since the

metamorphism of ultramafic rocks commonly takes place under conditions in which silica and aluminium are not present in abundance. This contrasts with a postulated situation where serpentine grains are present in a sandstone, and silica and aluminium are present in relative abundance.

3. Although the 7 Angstrom chlorite is normally considered a low temperature chlorite, there is some disagreement regarding the temperature at which 7 Angstrom chlorite undergoes a transition to 14 Angstrom chlorite. According to the discussion in Frey (1987), the temperature at which the transition takes place may range anywhere from 100 degrees celcius to over 200 degrees celcius. It seems likely that the transformation takes place within the zeolite facies of metamorphism, and hence it is not impossible that 7 Angstrom chlorites could in fact be metamorphic chlorites.

All evidence suggesting a diagenetic origin can clearly also be explained in terms of a metamorphic origin for chloritised serpentine grains, whereas it is less easy to explain the evidence for a metamorphic origin in terms of diagenesis. Thus the author favours metamorphosis at the source for the origin of these chloritised serpentine grains, although further study is clearly required.

The above discussion is significant because the dissolution of an A1 bearing silicate will require a different mechanism than one which does not contain A1.

Based on the hypothesis that chloritised serpentine grains were chlorite by the time they were incorporated into the mainland Formation, a model for their dissolution can be constructed, based on the work of Moncure et al. (1984), Siebert et al. (1984) and Surdam (1984). Surdam (1984) has convincingly argued that organic acids produced by the maturation of organic matter can greatly increase the mobility of Al within a system, by complexing the Al which allows a relatively low flow-through to remove the Al from the system. Moncure et al. (1984) and Siebert et al. (1984) have related this process to the development of secondary porosity through general observations of feldspar dissolution in sandstones. Development of secondary porosity through framework grain dissolution is accentuated by:

1. High initial permeability;
2. Increased relative thickness of shale relative to sandstone;
3. Increased organic content in the shale;
4. Abundant soluble grains.

This would be consistent with observations from the mainland Formation in that some of the samples with dissolved chlorite grains also contain relatively abundant quartz overgrowths and calcite cement, and are coarse grained, all of which suggest that the original material may have had a relatively high initial permeability. The fact that most of the samples with secondary porosity come either from the Low Point section or from sandstone packages interbedded with shales below the Low Point section is also significant, as true shale is not abundant within the main mainland and Three Rock Cove sections. Comment cannot be made on the organic content of the shales, however some organic material (graptolites) is certainly present.

The fact that grain edges are commonly preserved, and grain cores dissolved, suggests that the more magnesium rich cores were particularly prone to solution in this diagenetic regime.

It seems clear that the dissolution of chlorite grains was a relatively late event, given the lack of compaction of the pores. The association in one case (ML 26) of dissolution of chlorite grains with very limited dissolution of feldspars, and decarbonitisation suggests that in this case the dissolving solutions were acidic, perhaps indicating association with maturation of a relatively organic-rich juxtaposed shale. However, in all other samples where dissolution of chlorite has been observed, it has not been associated with decarbonitisation and hence the dissolving solutions are likely to have been predominantly alkaline.

The lack of secondary porosity of this type in the rest of the mainland Formation, and in the American Tickle Formation can be explained by a combination of the following factors:

1. Low initial permeability of most samples;
2. Lack of juxtaposition with organic rich shales in most parts of the American Tickle and Mainland Formations;
3. Juxtaposition with shales which are insufficiently organic rich.

Thus the development of this late secondary porosity is considered to have little regional significance. According to Siebert et al. (1984), the permeability will not have been significantly enhanced, and even the most porous sample encountered in this study has a porosity of less than 3%. It is interesting to note, however, that the sandstones most likely to be juxtaposed with shales of sufficient thickness are those in the upper parts of the Goose Tickle Group, which might be expected to be located offshore.

Summary of Paragenetic Sequence

In summary, samples from both the mainland and American Tickle formations show a generally similar paragenetic sequence. The sequence can be summarised as follows (from earliest to latest):

1. Quartz Overgrowth / K-Feldspar Overgrowth;
2. Feldspar dissolution and replacement;
3. Pore-filling carbonate cement;
4. Dissolution of chlorite grains and in some cases carbonate cement;
5. minor growth of authigenic clay minerals (chlorite, illite);

It is interesting to note that two phases of framework grain dissolution are implied here, with the early phase leaving chloritised serpentine grains intact, and later phases largely leaving feldspars intact.

Comparison with Hibernia Formation

Prior to the initiation of this study, Mobil expressed an interest in a comparison of the paragenetic sequence in the Hibernia Formation (Upper Cretaceous-Lower Jurassic) off the coast of eastern Newfoundland. This has been described by Brown et al. (1989).

The initial lithology, quartz arenite, of the Hibernia Formation, is considerably different from the wackes of the Goose Tickle Group. In contrast to the Goose Tickle Group, the Hibernia Formation contains little or no matrix, no volcanic fragments, and very little feldspar.

In the Hibernia Formation authigenic quartz occurs as syntaxial overgrowths, but in far greater quantities than in the Goose Tickle Group, which is probably indicative of the higher initial permeability of the Hibernia Formation in comparison with the Goose Tickle Group.

Quartz overgrowth formation in the Hibernia Formation was followed by carbonate cementation, reflecting a change in conditions to higher pH and temperature. Brown et al. (1989) noted that carbonate cementation was accompanied by silica and feldspar replacement, and suggested that it occurred prior to significant grain rearrangement through compaction. In contrast, it has been suggested here that carbonate cementation occurred subsequent to compaction in the Goose Tickle Group. Decarbonatization is responsible for most of the porosity in the Hibernia Formation, and authigenic clay minerals have grown in some of the secondary pores. Brown et al. (1989) suggested that low pH fluids derived from the underlying overpressured section or the maturation of organic matter and formation of corrosive fluids was responsible for decarbonitization in the Hibernia Formation. As described above, dissolution of carbonate cement was only observed in one sample from the Mainland Formation.

Dissolution of framework grains has been observed both in the Goose Tickle Group and in the Hibernia Formation, but the majority of dissolved grains in the Goose Tickle Group are mafic/ultramafic grains which are not present in the Hibernia Formation. Although organic maturation is suggested to have been responsible for the formation of fluids which dissolved grains in the Goose Tickle Group, it is suggested that these were weak and generally non-corrosive, and only attacked the least stable grains in the system.

Hydrocarbon migration and accumulation in the Hibernia Formation occurred after decarbonitization, as indicated by bitumen lined secondary pores (Brown et al. , 1989), whereas there is no evidence of substantial hydrocarbon migration in the Goose Tickle Group.

Clearly, from the above discussion, there is little useful comparison to be made between the Goose Tickle Group and the Hibernia Formation, since the two most important features of the Hibernia Formation, decarbonitisation and hydrocarbon migration/emplacement have apparently not occurred to any significant extent in the Goose Tickle Group.

Regional Diagenetic Considerations

Regional alteration patterns and Conodont Colour Alteration Indices

Regionally, the degree of alteration of the Goose Tickle Group increases from the Port au Port area to the tip of the Northern Peninsula, with American Tickle sandstones being more indurated and less friable than mainland sandstones. The most obvious effects of the higher grade of diagenesis in the Northern Peninsula are a tendency towards greater percentages of matrix, some of which is probably pseudomatrix, and some of which is likely recrystallised primary matrix. There also appears to be a greater tendency for replacement of grains by carbonate. in the most highly altered samples collected from near the contacts with transported terranes, albite overgrowths are commonly formed parallel to the main plane of foliation in the rocks and are derived from pressure solution related to cleavage formation.

These observations are consistent with the conodont colour alteration indices (CAI's) for the region reported by Nowlan and Barnes (1987). Conodonts from units both younger (Long Point Group) and older (Table Head Group) than the mainland Formation in the Port au Port Peninsula area show CAI's of I (immature).

CAI's from the Table Head Group underlying the American Tickle Formation in the Northern Peninsula show CAI's from 5 to 5.5 (overmature).

In the central part of the region, CAI's from the Table Head Group underlying the American Tickle Formation at Table Cove are 2+ (mature), as are values from the Daniel's Harbour Member of the American Tickle Formation at Daniel's Harbour, several kilometers south of Table Cove. These intermediate values are reflected in the fact that the Table Cove and Bellburns localities are more indurated than the mainland sandstones, but in general do not show elevated abundances of matrix, or albite overgrowths.

It should be noted that the author considers the CAI data from the mainland and Table Cove areas as directly comparable, since neither of these localities is near the frontal thrust of a transported terrane. The values obtained by Nowlan and Barnes (1987) from the Northern Peninsula are high because they were collected from localities closer to the frontal thrust of the Hare Bay Allochthon. However, the author collected samples from all over the Northern Peninsula, and all show higher degrees of alteration than the mainland and Table Cove areas, consistent with the regional isopleths drawn by Nowlan and Barnes (1987).

Nowlan and Barnes (1987) did not attribute the north-south temperature anomaly to any effects of the Taconic or Acadian orogenies, because of the fact that CAI's decrease rapidly away from the margins of the allochthonous terranes, suggesting that these did not extend much further than their present areal limits. Nowlan and Barnes (1987) instead attributed the pattern to the track of a Mesozoic hotspot.

An alternative explanation is that the area could have been covered by post-Ordovician sediments which have subsequently been eroded, but there are no erosional remnants of such sediments. The higher degree of alteration in the Northern Peninsula area appears to coincide with a higher degree of deformation, and rocks in this area display a prominent cleavage. Other differences exist between the Hare Bay and Humber Arm allochthons, including the lack of a Lower Head Formation equivalent in the Hare Bay Allochthon, the lack of a mafic volcanic cap to ophiolitic rocks in the Hare Bay Allochthon, and the older age of the metamorphic aureole to the ophiolitic rocks in the Hare Bay allochthon.

There are clearly regional structural/tectonic differences between the Northern Peninsula and the area of

Bonne Bay and south, which have yet to be explained, however none of these features seem likely to have been generated by a travelling Mesozoic hotspot. Therefore the author favours a more general version of the alternative explanation postulated by Nowlan and Barnes (1987), that the area was previously buried either under deposited sediments, or more likely (given the deformation characteristics) under an extensive high thrust slice, which has subsequently been eroded. it is interesting to note in support of this, that Hendrik (1990) has found evidence (from analysis of fission track data) for Late Paleozoic burial of the Northern Peninsula.

Regardless of the cause of the regional CAI pattern, it does seem to be reflected in the degree of alteration of the sandstones, and is therefore useful because it allows one to predict, in a qualitative manner, how the relatively unaltered Mainland Formation might appear at a higher diagenetic grade. It is possible to do this because of the clearly demonstrated relative petrographic homogeneity along the basin as demonstrated in section 2.6. It is clear that overmaturation of organic material within the American Tickle Formation in the Northern Peninsula has been insufficient to dissolve either framework grains or carbonate cement, and hence it is unlikely that sandstones offshore of either mainland or the American Tickle Formation in the Table Cove/Bellburns area have developed substantial secondary porosity. A few sandstone beds in the offshore mainland Formation may have developed secondary porosity through dissolution of chlorite grains but (as discussed above), the development of this porosity depends on the fortuitous association of a number of different factors, and will not significantly enhance permeability. In any case, given the abundance of phyllosilicate grains generally, 7% would be the maximum porosity expected through this process.

<u>Significance of variations in shale chip diagenesis</u>
Fluorescence microscopy shows that organic material in the abundant detrital shale chips of the Goose Tickle Group displays varying degrees of alteration. Some of this variability is due to the regional variations of diagenetic grade in the host sandstones as described in the previous section. Thus the Mainland Formation, especially at its top, shows the greatest abundance of yellow fluorescing brown-red organic material in shale chips, whereas shale chips from sandstones of northern areas are completely black and non-fluorescent.

However, shale chips within the Mainland Formation show variability in the degree of alteration even within a single sample, suggesting a variety of sources for the chips. The more altered chips have clearly undergone compaction and alteration prior to their incorporation in the sandstones. This is attributed to the likelihood that they were probably eroded from the eastern basin margin.

Fluorescing organic material is present in some of the shale chips from the Mainland Formation. The yellow fluorescence, and laminar structure most resemble the maceral lamalginite (a liptinite maceral, see Hutton, 1991). The fairly intense fluorescence, and the yellow colour suggest that the least altered shale chips have a thermal alteration index of below 2, suggesting that they are below the oil window (Tissot and Welte, 1984).

It is not impossible that the more highly altered shale chips or their original source might have acted as a source of oil for reservoirs in the area. These possibilities will be discussed further in section 2.10.

<u>Basin configuration and diagenesis</u>
Basin configuration with associated heat flow and hydrogeological patterns could also have affected diagenesis of sandstones of the Goose Tickle Group. According to Bjorlykke (1988), porewaters in sedimentary basins have four different origins:

1. meteoric water flowing into the basin;
2. porewater forced upwards by the compaction of sediments;
3. water released by dehydration of minerals;
4. water released during metamorphism beneath the sedimentary basin.

The possibility of large scale convection currents leading to temperature or geochemical anomalies in the preserved part of the basin can probably be excluded because of the abundance of impermeable siltstone and mudstone layers between sandstone beds which would have impeded the circulation of convection currents (see Bjorlykke, 1988). There is also no indication that the floor of the basin was metamorphosed, although carbonate rich solutions which provided the late carbonate cement could have been derived from pressure solution of underlying carbonates, as was suggested for the Hibernia Formation by Brown et al. (1989). Therefore meteoric waters, waters released by compaction of the sandstones and their interbedded shales, and water released during chemical reactions are the most likely sources of porewaters for the Goose Tickle Group. This is consistent with the paragenetic sequence inferred above from petrographic evidence.

<u>Overall Reservoir Potential and Relationship to Potential Source Rocks</u>
In order for a viable play to exist five conditions must be met in a particular area (modified from Allen and Allen, 1990). These are:

1. The presence of an effective reservoir;
2. A regional topseal to the reservoir;
3. The presence of traps;
4. A source for petroleum.
5. The timely relationship of the above factors.

The discussion of the above factors will be concerned only with the Goose Tickle Group and related units as necessary, recognising that reservoirs may exist in the platform carbonates, and sources may exist in several shale units in the area (Sinclair, 1990).

1. Reservoir: Clearly, from the discussions throughout this document, the presence of an effective reservoir in the Goose Tickle Group cannot be demonstrated. Substantial thicknesses of sandstones exist, particularly in the mainland area, and many of these are coarse-grained. Despite the fact that turbidites can be good reservoirs (North, 1985), they are very variable, and the lack of porosity in these particular examples makes them unsuitable reservoirs. The only potential for reservoir capacity was encountered at the top of the Mainland Formation, but the extent of porosity offshore must be considered in doubt.

2. Regional Topseal: If, as the author has inferred, both the mainland and American Tickle Formations are fining upward, it is possible that in both cases a regional shale topseal exists.

3. Presence of traps: No obvious updip stratigraphic traps exist or are postulated within the Goose Tickle Group. In fact, it should be noted that generally the configuration of the Goose Tickle Group is that the coarsest updip sandstones are exposed onshore. Possible structural traps include shale melange at the bases of the allochthons, and traps related to major faults in the area, such as the Ten Mile Thrust. The way in which fault related traps might be developed is unclear, without more information on the faults themselves, and on facies variations offshore.

4. Source Rocks: Based specifically on this research and the author's knowledge of the tectonic setting and provenance of the mainland and American Tickle sandstones, three possible source rocks should be considered:
a) Organic rich layers in the American Tickle Formation. Despite having been deposited in an anoxic environment, these are unlikely to be good source rocks because the layers are too thin, they are interbedded with impermeable siltstones, and, in the Northern Peninsula, they are overmature.
b) The dominantly sandy Mainland Formation contains little true shale in its type section, and anoxic conditions did not prevail during its deposition, but at the structurally complex top of the section green shales are abundant. The organic content of these is unknown, and they are not in a suitable downdip direction to have supplied oil to any reservoir in the Goose Tickle Group. In addition, given the CAI's for the area, they may not have reached sufficient maturity for the generation of oil.
c) The presence of 'extrabasinal' shale chips in the Goose Tickle Group suggests that the uplifted eastern margin of the foreland basin is most likely to have been floored by shales similar to those

which are now found in the the middle Arm Point Formation as well as in melanges at the base of the Humber Arm and Hare Bay Allochthons. There is no evidence from the sandstones that shale chips have generated hydrocarbons subsequent to their incorporation in the sandstones. However some of these shale chips do contain considerable organic material, as do their inferred sources in the allochthons (Botsford, 1988).

5. Timely Relationships of the Above Factors:
Although the poor reservoir quality of the Goose Tickle Group almost makes it redundant to consider this aspect, the fact remains that sources identified in the preceding discussion might have fed other reservoirs, and in the interests of completeness, the discussion is continued.

The only source requiring further discussion is c) in the preceding section. The Arenig Middle Arm Point Formation (in the Humber Arm Allochthon) is a time equivalent of parts of the St. George Group, and was deposited in deep water during the transition from passive margin to foreland basin. Equivalent lithologies may therefore, prior to uplift and incorporation in the allochthon, have existed in a suitable down-dip position to allow for oil migration into the platform carbonates. This suggestion is given some credence by the findings of Sinclair (1990) and Weaver and Macko (1990), who identified the source of oil in the Humber Arm Allochthon as black shales within the Cow Head Group, a partial lateral equivalent of the Middle Arm Point Formation.

Sinclair (1990) thought it unlikely that shales in the allochthonous terranes could have acted as sources to reservoirs in the foreland basin proper, however, equivalents to these shales were once laterally gradational with the St. George group and could have acted as early sources of hydrocarbons. Problems with this hypothesis include the question of whether the shales could have reached sufficiently high temperatures prior to uplift in order for the generation of hydrocarbons to take place. This is a difficult question to answer, but it seems likely that they had undergone some alteration at a relatively early stage, judging by the presence of previously altered shale chips in sandstones of the Goose Tickle Group. However, according to Sinclair (1990), the development of significant porosity in the parautochthonous carbonates did not take place until the Silurian/Devonian Acadian Orogeny, by which time the potential sources were no longer in a down-dip position.

Shales of the eastern basin margin would have originally been positioned up-dip and not down-dip of the foreland basin sandstones and therefore are considered unlikely sources of hydrocarbons in the mainland and American Tickle formations.

<u>Other Potential Reservoirs in western Newfoundland</u>
Other potential reservoirs in western Newfoundland which might be investigated include the Clam Bank Formation (Silurian/Devonian) and the Lower Read Formation (allochthonous, Arenig-Llanvirn).
The Clam Bank Formation at its type section has been investigated by the author as part of another project and is a minimum of 630 m thick, with neither base nor top exposed. Lower parts of the section consist of peritidal limestones and shales interbedded with red siltstones and minor sandstones. These pass transitionally upward through red siltstones to about 200 m of friable, thick- to very thick-bedded medium- to coarse-grained red sandstones and pebble conglomerates. Although the sandstones of the Clam Bank Formation appear from hand specimen to have some reservoir potential, Sinclair (1990) and Fleming (1970) have suggested that because the updip termination of the unit is exposed, the likelihood of it being a significant reservoir is small.

The Lower Head Formation is interesting because, although it is similar in many respects to the Goose Tickle Group (Quinn, 1992), it is associated with oil in the Parsons Pond area north of Bonne Bay (Map 3). The Lower Head Formation is dominated regionally by massive medium- to coarse-grained sandstones, and although the formation is petrographically distinguishable from the Goose Tickle Group, it is nevertheless rather similar.

Several factors (which require further investigation) might contribute to the ability of the Lower Head Formation to hold oil:

1. The massive sandstone facies in the Lower Head Formation contain abundant fluid escape structures, which are not common in the Goose Tickle Group - thus at least some parts of the Lower Head Formation may have had a higher early porosity generated by the removal of fines in this manner. However, fluid escape structures now visible in outcrop are cemented by calcite.

2. Serpentinised chlorite grains, which are present in the Lower Head Formation (see figure 10 for chemical compositions) could have been dissolved in the same manner as outlined for the Goose Tickle Group. Parts of the Lower Head Formation do contain shale packages of significant thickness (notably at the coastal section south of the village of Portland Creek, see Map 3).

Conclusions

As a result of this study, the following conclusions have been reached:

1. Areas of sufficient net sand content to suggest reservoir potential occur in only two zones of limited extent (the Table Cove/Bellburns, and mainland areas).

2. Estimates of the offshore extent of the Mainland Formation and the American Tickle Formation are inaccurate because of poor structural control onshore, but regional facies relationships suggest generally sand-poor deposits are to be expected offshore.

3. The low visual porosity in both of the identified sand-rich zones suggests that neither has reservoir potential. The main controlling factor is the lack of porosity, which is ultimately controlled by high initial matrix content and poor sorting.

4. The upper part of the mainland Formation contains the most porous rocks, with porosity being generated through the dissolution of chloritised serpentine grains probably by fluids generated through the maturation of organic matter in associated shales.

5. Extrapolations from more northerly areas at higher diagenetic grade suggest that deeper offshore burial of lithologies observed in the sand-rich zones onshore is unlikely to have produced substantial secondary porosity.

6. The presence of abundant organic rich shale chips as fragments in the Mainland and American Tickle Formations suggests that suitable source rocks did exist along the eastern margin of the foreland basin, and regional relationships suggest that the best analogues for these are to be found in the Lower Ordovician shales of the Humber Arm Allochthon. However, the timely relationship between maturation of organic matter in these rocks and the development of reservoirs has not been demonstrated.

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Appendix 1 General Map Locations

Location Map (pdf - 95kb)

Map 1 Port au Port Peninsula (pdf - 135kb)

Map 2 Bay of Islands (pdf - 218kb)

Map 3 North of Bonne Bay (pdf - 159kb)

Map 4 Hare Bay and Pistolet Bay (pdf - 190kb)