Basin Evolution in Western Newfoundland: New Insights from Hydrocarbon Exploration

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ABSTRACT

The Humber Zone is the most external zone of the Appalachian orogen in Western Newfoundland. It records multiphase deformation of the Cambro-Ordovician passive margin and of the Ordovician to Devonian foreland basins by the Taconian, Salinian and Acadian orogenic events.

The recent phase of exploration drilling has provided new evidence for structural and stratigraphic models of Western Newfoundland. The first well, Port au Port #1, supported the hypothesis that the Round Head Thrust had an earlier extensional history prior to the Acadian compressional inversion that created the present-day structural high of the Port au Port Peninsula. The well tested a small anticline caused by a footwall shortcut fault from the Round Head Thrust. The second well, Long Point M-16 was drilled at the northern tip of Long Point to test a triangle zone identified by previous workers. This well demonstrates that the frontal monocline at the western edge of the triangle zone is elevated by a stack of imbricate thrusts composed of rocks of the Taconian allochthon and compressional basement-involved faults which have uplifted the Cambro-Ordovician carbonate platform.

The structural model developed in the Port au Port area with the aid of these wells has been extended throughout the Humber Zone in Western Newfoundland. Changes in structural style illustrated by regional cross-sections suggest that prospective trap geometries are only developed in the southern and central parts of the region.

The reservoir model invoked from the exploration programme invokes exposure and karsting of the footwalls of extensional faults developed as the carbonate platform collapsed during a Middle Ordovician hiatus, the St. George Unconformity. Structural relief became more pronounced as extensional collapse continued through the Middle Ordovician. These structurally high fault footwalls became the focii for dolomitizing and mineralizing fluids that utilized major faults as fluid conduits during the Devonian. These fluids deposited sulphide ores, created zebra and sparry dolomite and some sucrosic hydrothermal dolomites in the St. George Group and the Table Point Formation.

The reservoir model, maturity and source rock data and the structural models have been combined with seismic and onshore surface geology. This enables the prospectivity of the Western Newfoundland Cambro-Ordovician playtrend to be evaluated for further exploration.

INTRODUCTION

Geological Setting

The west coast of Newfoundland lies within the northeast Canadian Appalachians and has been affected by a number of orogenic events in a complex geological history, punctuated by the opening and closing of the (proto-Atlantic) Iapetus Ocean. The Canadian Appalachians have been subdivided into five tectonostratigraphic domains by Williams (1979); the westernmost domain, the Humber Zone, includes western Newfoundland and the northern Gaspé Peninsula in Quebec.

The earliest sedimentary sequence in the Humber Zone is the Late Proterozoic - Early Cambrian siliciclastic rift sequence (the Labrador Group, Figs 1and 2), deposited as the Iapetus Ocean formed. Subsequent to rifting, a stable, eastward sloping continental margin developed from Greenland to West Texas. A basal clastic sequence and a series of upward-shoaling carbonate cycles were deposited on this passive margin from the middle Cambrian through Early Ordovician (Labrador, Port au Port and St. George groups). A steep continental shelf break and abyssal plain existed some 100km to the east of the present coast of western Newfoundland. The Cow Head Group breccias (shelf break) and deep water shales farther to the east were deposited as time equivalent facies of the shelf sequences (see Figure 4). Deposition of this stable platform in West Newfoundland was terminated during a major eustatic sea level drop (Sauk III/Tippecanoe) culminating in a regional unconformity. This St. George unconformity has been interpreted by Jacobi (1981) and

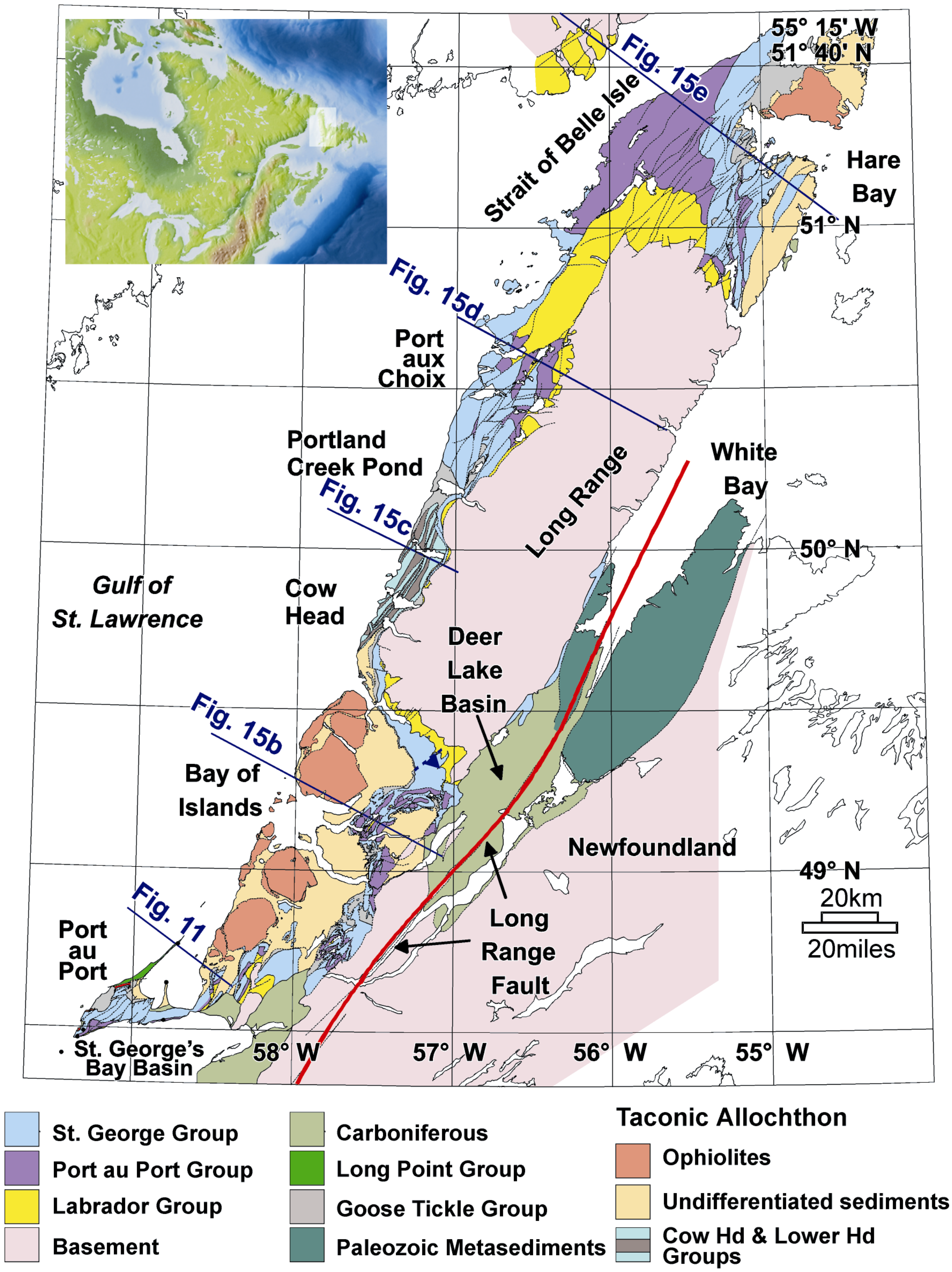

Fig. 1. Surface geology compilation map of W. Newfoundland based on work by Knight (1991, 1994), Stockmal and Waldron (1993), Palmer (1995), Williams and Cawood (1989). The locations of regional structural cross-sections are indicated.

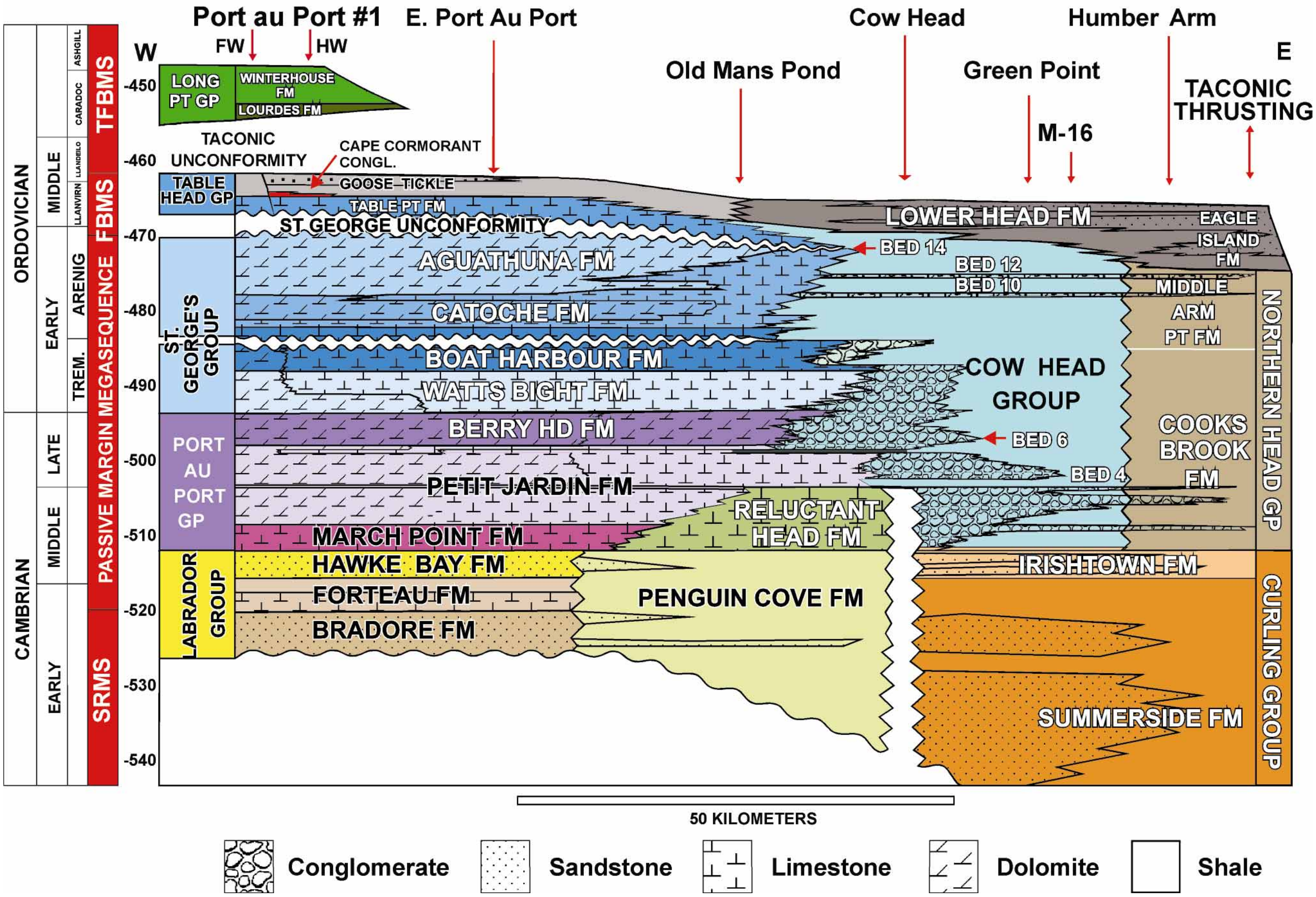

Fig. 2. Chronostratigraphic summary diagram of W. Newfoundland Cambro-Ordovician strata. Lithostratigraphic units are coloured and the ornamentation indicates the dominant lithology. The age ranges of the megasequences defined are shown to the right of the geological stages; SRMS, Syn-Rift Megasequence; FBMS, Flexural Bulge Megasequence; TFBMS, Taconic Foreland Basin Megasequence. Dating of the strata is based on paleontological data from James and Stevens (1986), Williams et al. (1987), Botsford (1988), Williams and Stevens (1988), Stenzel et al. (1990), Knight et al. (1991), Stait and Barnes (1991), Cowan and James (1993), Knight and Cawood (1993), Burden and Williams (1995, 1996). The time scale used is that of Tucker and McKerrow (1995).

Knight et al. (1991) to be related to the migration of the flexural forebulge of the Taconic foreland basin. The unconformity can be recognised today from Greenland through western Newfoundland (St. George Group), Quebec (Romaine Formation), Illinois (Knox Formation), Kansas and Oklahoma (Arbuckle Formation) to Texas (Ellenberger Formation).

The Middle Ordovician Taconian Orogeny marked the closing of the Iapetus Ocean as the imbricated Humber Arm Allochthon was thrust westward onto the Lower Ordovician carbonate platform (Cawood and Suhr, 1992). The Humber Arm Allochthon is internally sub-divided into a series of structural slices, the uppermost one carrying the ophiolites of the Bay of Islands Complex. The lower and intermediate slices comprise the rocks of the siliciclastic dominated Humber Arm Supergroup which are the continental slope and rise correlatives of the Labrador, Port au Port and St. George groups. This effectively placed time-equivalent and immature potential source rocks onto the reservoir facies of the carbonate platform. The westward advance of the allochthon progressively caused westward migration of a peripheral bulge, extensional block fault collapse of the platform coeval with the SaukIII/ Tippecanoe sea-level drop, diachronous (westward younging) deposition of deeper-water carbonates and deposition of deep water syn-orogenic flysch derived from the allochthon.

The Humber Arm Allochthon is preserved today in an elongate structural low bounded to the north and east by granitic Grenville basement (Fig. 1). The Grenville is overlain unconformably by the Labrador to St. George groups on the north-western flank of the Long Range Mountains. To the south the low is bounded by a culmination of the Labrador, Port au Port and St. George's groups characterized by basement-cored, faulted anticlines (Fig. 1).

The Taconic orogeny was followed by tectonic quiescence during which the Middle to Upper Ordovician Long Point Group, deposited in a foreland basin setting. At its eastern limit the basal unit of the group, the Lourdes Limestone, was deposited unconformably on the western leading edge of the Humber Arm Allochthon.

The Salinic Orogeny further imbricated the allochthonous sequence causing additional displacement towards the west (Cawood et al, 1994). In addition it exposed the metamorphosed hinterland and deformed platform to the east. The Silurian Clam Bank and overlying Devonian Red Island Road formations are shallow water sand/shale sequences that are likely the foreland basin of the Salinic orogeny. A final westward push during the Devonian Acadian Orogeny created the triangle zone located offshore (Cawood and Williams, 1988; Waldron and Stockmal, 1991; Waldron and Stockmal, 1994) and caused the thick-skinned compressional faulting. Transtensional dextral reactivation of pre-existing basement faults (Bradley 1982) resulted in the development of successor basins with thick Carboniferous clastic fills in the Deer Lake and St. George's Bay basins (Fig. 1), (Knight 1983).

Exploration History

A number of shallow wells drilled in the 19th and early 20th centuries on the Port au Port Peninsula and at Parsons Pond (Fig. 3) produced small quantities of oil that were used locally for lubricative and medicinal purposes (Department of Energy 1989). In addition, a number of seeps containing live oil and bitumen staining in rocks were known from the Port au Port Peninsula, Parsons Pond, Humber Arm and Port aux Choix (Fig. 3 and Department of Energy 1989). Two wells were drilled by Golden Eagle on Shoal Point in the 1960's (Fig. 5), both abandoned but one well encountered minor quantities of oil. Until recently the only deep well in the region was drilled farther to the south in the sediments of the Carboniferous/Devonian Anguille Group by Unocal in the 1970's.

In this paper, we report the results from the latest round of hydrocarbon exploration in the area, including three exploration wells and both onshore and offshore seismic data. These data have allowed the development of models for structural trapping configurations, reservoir development and source rock maturation.

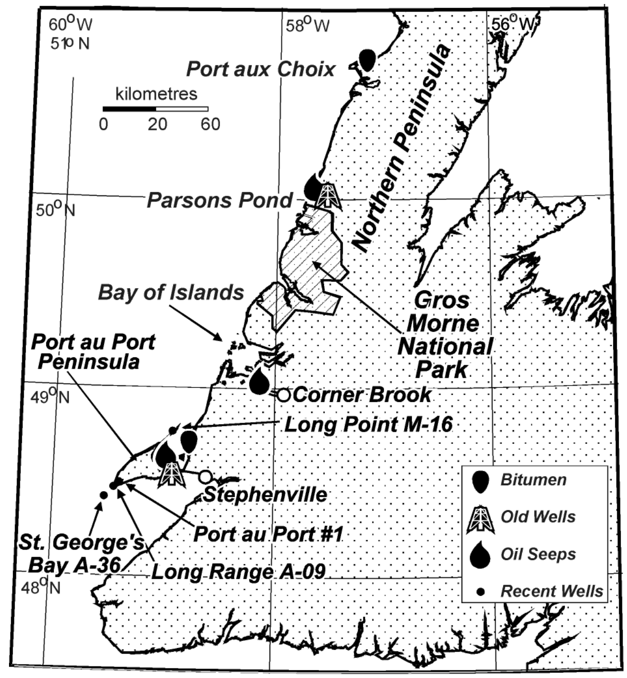

Fig. 3. Recent wells and hydrocarbon occurrences in the Humber Zone of W. Newfoundland based on data from Department of Energy (1989), Fowler et al. (1995) and Williams et al. (1998).

STRATIGRAPHY

The stratigraphic relationships in Western Newfoundland have been complicated by phases of tectonism in the Ordovician (Taconic, Williams and Stevens 1974), Silurian (Salinic, Dunning et al. 1990) and Devonian (Acadian, Cawood and Williams 1988). Coeval, highly diverse lithostratigraphic units that were originally 10's of kms apart are now juxtaposed across major faults. This has resulted in a plethora of stratigraphic nomenclature which has only been unravelled by detailed paleontological analysis (James and Stevens 1986, Botsford 1987, Cowan and James 1987, Williams et al. 1987, Williams and Stevens 1988, Stenzel et al. 1990, Knight et al. 1991, Stait and Barnes 1991, Knight and Cawood 1991). In this paper we describe the stratigraphy of western Newfoundland in relation to a proposed sequence stratigraphy of the strata; the megasequences are based on the major tectonic events and their related unconformities. Thus, whilst adhering to established lithostratigraphic nomenclature we discuss the stratigraphy in time sequence on a palinspastically restored base (Fig. 2). The chronostratigraphic summary diagram (Fig. 2) has been compiled by using data from published sources combined with proprietary data from the wells drilled in the recent phase of exploration.

The Syn-Rift Megasequence

The Syn-Rift Megasequence comprises the Bateau, Lighthouse Cove (Williams and Stevens 1969, not developed in West Newfoundland) and Bradore formations of the Labrador Group, (Schuchert and Dunbar 1934, Hiscott et al. 1984). These formations consist of sediments and volcanics deposited in the accommodation space created during the Late Proterozoic and Early Cambrian rifting of the Iapetus Ocean. The exact age of the basal unconformity beneath the Labrador Group, a regional seismic reflector, is poorly constrained due to the lack of fossils in these predominantly arkosic sediments. Williams et al. (1985) have suggested an approximate age of 620ma for the unconformity based on radiometric dating of correlative strata to the Lighthouse Cove volcanics. The upper boundary of the Syn-Rift Megasequence is placed at the base of the Forteau Formation (Schuchert and Dunbar 1934). The abrupt change from fluvial arkoses of the Bradore Formation through shallow marine reefal limestones of the Devils Cove member (Betz 1939) into the deeper marine Forteau Formation shales reflects the onset of thermal subsidence following the cessation of active rifting (Williams and Hiscott 1987). Supporting evidence for this model is inferred from rapid thickness changes in the lower Labrador Group whereas the Forteau and younger formations show only gradual, regional changes in thickness (Knight and Cawood 1991, fig. 16). The Bradore Formation was much thicker in the hangingwall of the Round Head Thrust in the Port au Port#1 well than in the outcrops 50km to the east. The distal equivalents of the lower Laborador Group in the Syn-Rift Megasequence are the Summerside Formation (Weitz 1953, Botsford, 1987) and the Blow-Me-Down-Brook Formation (Stevens, 1965) both of which are only seen within the Humber Arm Allochthon.

Passive Margin Megasequence

The Passive Margin Megasequence commences with the Forteau Formation (Schuchert and Dunbar, 1934) which is dominated by marine shales (Fig. 2). This is overlain by the shallow marine sands of the Hawke's Bay Formation (Schuchert and Dunbar 1934) (Fig. 2). The near distal equivalent is the Penguin Cove Formation (Knight and Boyce 1991), which outcrops in the eastern part of the para-autochthon and the Salinic deformation belt. The Penguin Cove is dominated by shales and thin-bedded sandstones interbedded upward with quartz arenites (Knight and Boyce 1991). The far distal equivalents, the upper Summerside Formation (Weitz 1953) and the Irishtown Formation (Brueckner 1966), are both dominated by shales with thin sandstone turbidites and thick channel-bound quartz arenites. These are exposed only within the Humber Arm Allochthon (Figs. 1and 2).

Above the clastics are carbonates which dominate the megasequence. The carbonates are divided into 2 groups; the Cambrian Port au Port Group (Chow and James 1987), and the early Ordovician St. George Group (Knight and James 1987). The Port au Port Group comprises 3 formations; the March Point, Petit Jardin and Berry Head (Chow and James op. cit.). The March Point Formation is predominantly shale and shaly limestones; it represents a transgressive phase that terminated sand deposition. The Petit Jardin Formation is dominated by oolitic and peritidal dolomites with intercalated shaly carbonates that represent floods over the platform; the youngest of these produces a good seismic reflector.

The St. George Group is sub-divided into the Watts Bight, Boat Harbour, Catoche and Aguathuna formations (Knight, 1991). The Watts Bight and Catoche contain burrowed, thrombolitic and peloidal grainstone facies indicative of sub-tidal depositional environments. The Boat Harbour and Aguathuna formations contain fenestral and cryptalgal dolomudstones representing peritidal environments. Near to top of the Boat Harbour formation a 1-2 ma hiatus occurs at a disconformity (Knight et al. 1991, Fig. 2).

The distal equivalents of the Port au Port and St. George groups are the Cooks Brook and Middle Arm Point formations (Stevens 1965, Brueckner 1966, Botsford 1987) of the Humber Arm Allochthon. These units have been transported at least 100 km west from their original site of deposition (Stockmal et al. 1995). Proximal peri-platform off-margin facies are the well-documented rocks of the Cow Head Group (James and Stevens 1986) which include spectacular debris flows derived from the platform. The Cow Head Group is only exposed in the central part of the Northern peninsula (Fig. 1).

In the para-autochthonous Salinic deformation belt east of the Bay of Islands (Fig. 1), the time equivalent formations are represented by the Reluctant Head Formation (Lilly 1963), and the Weasel Group interpreted by Boyce et al. (1992) as a ramp margin that contrasts with the rimmed to bypass margin west of the Cow Head Group (James and Stevens 1986, James et al. 1989).

The Flexural Bulge Megasequence

The St. George unconformity separates the St. George Group from the overlying Table Head Group and defines the boundary between the Passive Margin and Flexural Bulge megasequences. This unconformity represents an approximate hiatus of 4-5 ma on the Port au Port peninsula (Burden and Williams 1995) and is interpreted to be the result of platform collapse due to extensional faulting of a Taconic migrating peripheral bulge (Knight et al.

1991). Locally complex stratigraphic relationships are related to dolines both above and below the unconformity. The subsidence has resulted in the localised deposition of peritidal dolo-laminites above the unconformity which previously have been mapped as the upper Aguathuna Formation (Knight et al. 1991). In the Humber Arm Allochthon the Cow Head Group is unconformably overlain by the Lower Head Formation (Williams et al. 1985). Quinn (1995) interprets the Lower Head Formation to be rapidly deposited during syn-depositional tilting and erosion of the underlying Cow Head Group implying only a small hiatus at this unconformity. We propose that the hiatus represented by the unconformity decreases in magnitude eastwards on the paleo shelf break and was less prone to emergence as the peripheral bulge migrated through. Knight et al. (1991) have suggested that the erosional debris of Beds 12 and 14 in the Cow Head Group are linked to the development of the unconformity.

The Table Head Group includes the Table Point Formation (Klappa et al. 1980), a series of shallow to deep subtidal limestones of variable thickness that infill the karsted paleo-relief created during platform collapse (Stenzel et al. 1990). The Table Point is overlain by the Cape Cormo-

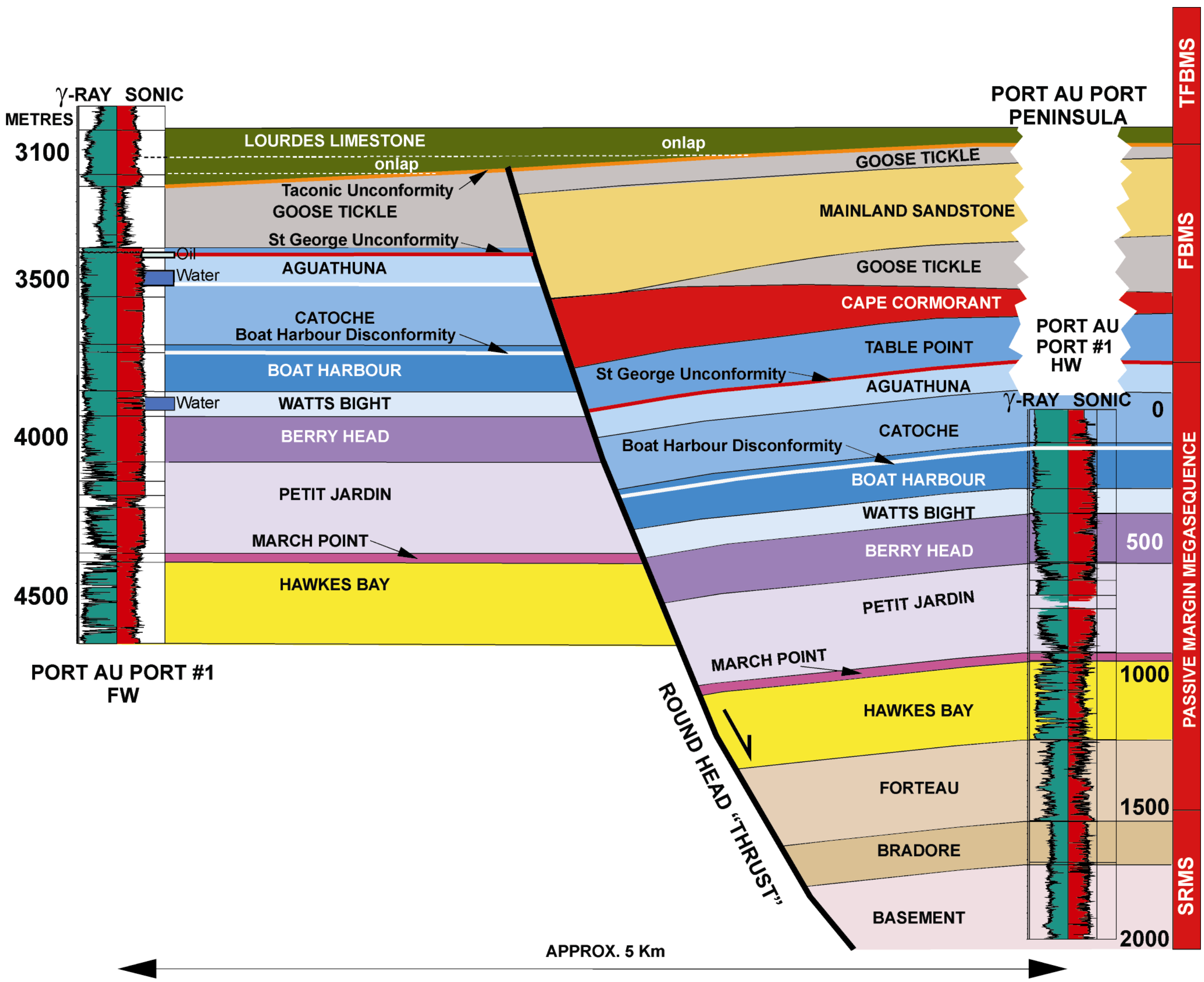

Fig. 4. Stratigraphic reconstruction of the Round Head Fault at end Lourdes time. Logs from the footwall portion of the Port au Port #1 well have been used without modification. Logs from the hangingwall portion of the Port au Port #1 well were corrected for 40^{o} NW dips to create true stratigraphic thickness logs prior to inclusion in the correlation. The Port au Port #1 well spudded in the Catoche Formation and the thickness of the overlying units have been reconstructed using published data from the Port au Port Peninsula outcrops (Knight et al. 1991, Stenzel et al 1990, Stait and Barnes 1991, Quinn 1995).

rant Formation, conglomerates which were deposited adjacent to active fault scarps as submarine talus fans. The conglomerates contain clasts as old as Cambrian derived from the Port au Port and St. George Group carbonate platform of the fault footwalls. Away from the fault scarps the laterally equivalent Table Cove Formation was deposited, a sequence of deep marine shales and thin limestones that represent the final collapse and drowning of the carbonate platform (Stenzel et al. 1990). The Table Head Group is conformably overlain by the Goose Tickle Group, a muddy flysch derived from the Taconic thrust belt to the east. The Goose Tickle Group includes the Black Cove Formation, American Tickle Formation, Mainland Sandstone and the Daniels Harbour Member (Stenzel et al. 1990). The same stratigraphic relationships can be observed to the east in the para-autochthonous Salinic deformation belt.

The Goose Tickle and Table Head groups are thinner in the Port au Port #1 well (185m and 15m respectively) than at outcrop on the west coast of the Port au Port Peninsula (at least 1000m, Quinn 1995, Stenzel et al. 1990). The significance of this change in thickness of the Flexural Bulge Megasequence can be better appreciated on a stratigraphic reconstruction at end Lourdes time (Fig. 4). To accommodate strata, the reconstruction shows that the Round Head Fault originally had an extensional offset of at least 1000 m by the Late Llanvirnian. Stenzel et al. (1990) and Waldron et al. (1993) both postulated that the Round Head Fault had significant extensional relief in the early Ordovician. Waldron et al (1993) also noted the spatial relationship between the thickest development of the Cape Cormorant Conglomerate and the immediate hanging wall of the Round Head Fault. However, this model had remained speculative as the stratigraphic units of interest (Table Head and Goose Tickle Groups) in the footwall of the now inverted Round Head Fault are not exposed (Figs 4, 8). The Port au Port #1 well confirms the early extensional history and constrains the stratigraphic thickness of these units in the footwall (Figs 8, 9). The thick turbidite fan sands of the Mainland Sandstone (Quinn, 1995), in the immediate hangingwall of the Round Head Fault (Waldron et al. 1993) represent infill of a starved, fault bounded basin developed during the deposition of the Cape Cormorant Conglomerate.

Within the Humber Arm Allochthon the Lower Head Formation (Williams et al. 1985), is correlative with the Table Head Group and the lower part of the Goose Tickle Group. The Lower Head Formation is a more sand dominated flysch sequence but is older than the Goose Tickle Group (Quinn 1995). This difference in age is consistent with the east to west emplacement of the Humber Arm Allochthon. Paleogeographically, the Table Head Group only appears to have developed above the pre-existing Cambro-Ordovician platform. This may have been due to the paleo-bathymetry of the flexural bulge which would have shown a significant deepening eastwards across the platform margin thereby inhibiting carbonate deposition.

The Taconic Foreland Basin Megasequence

Above the Taconic flysch lies another major hiatus of approximately 10-15 ma duration, here termed the “Taconic Unconformity” which marks the emplacement of the Taconic allochthons onto the mid to outer portion of the old shelf margin. Burden and Williams (1995) were able to identify this unconformity between the Lourdes Formation and the Goose Tickle Group in cuttings from the Port au Port #1 well. The Taconic allochthons include the Humber Arm Allochthon, which comprises the distal equivalents of the syn-rift and passive margin megasequences. The allochthons were probably emplaced in a submarine environment as there evidenced by sediment deformation and mixing of flysch with the indurated shales and ribbon limestones of the Humber Arm Allochthon on the eastern shore of Port au Port Bay.

The Lourdes Formation, the lowest unit of the Caradocian Long Point Group (Fig. 2) was deposited above the Taconic unconformity. These shallow marine limestones have been interpreted by Stockmal et al. (1995) as reflecting the position of the forebulge crest of the Taconic orogen. The Lourdes Formation is overlain by the Winterhouse and Misty Point Formations (Quinn, 1998), an interbedded series of shales, sandstones and rare thin limestones. These formations represent the fill of the Taconic Foreland Basin. The Long Point Group is only exposed on the Port au Port peninsula (Fig. 5) although offshore seismic data and seabed geology maps (Sanford and Grant 1990) indicate that the group is present in the Gulf of St. Lawrence. The Lourdes formation is significantly thicker (180m) in the Port au Port#1 well than at outcrop (75m). This is due to the presence of two additional, basal members confirmed from biostratigraphy in the cuttings (Burden and Williams 1995). The westward thickening due to these additional stratigraphic units is compatible with eastward onlap onto the Humber Arm Allochthon but is inconsistent with the interpretation of Stockmal et al. (1995) of deposition on the eastern flank of the Taconic peripheral bulge (op. cit., fig. 10).

The Salinic Foreland Basin Megasequence

Another major unconformity separates the Taconic and Salinic Foreland Basin Megasequences. This is manifested as a time gap of ca. 30 ma between the Misty Point Formation and the Clam Bank Group; there is no obvious angular unconformity. The Salinic Foreland Basin Megasequence includes the fluvial sands and shales of the Pridolian Clam Bank Formation and the red beds of the Emsian Red Island Road Formation (Williams et al. 1996).

The Successor Basin Megasequence

The youngest preserved sediments in the area are the Carboniferous strata of the Anguille, Codroy and Barachois groups. These are dominantly fluvial sandstones, silts and shales and localised lacustrine source rocks with a regionally important marine evaporite sequence that has well developed pillows and domes in St. Georges Bay (Knight 1983). The Carboniferous rests unconformably on the peneplained generally north to northwest dipping Lower Paleozoic rocks exposed in the hangingwall of the Round Head Thrust on the Port au Port peninsula. The hiatus represented by the unconformity encompasses much of the late Devonian and post-dates the Acadian orogeny.

THE EXPLORATION PLAY CONCEPT

Since 1991 a large amount of seismic data has been acquired both onshore and offshore in the Humber Zone of Western Newfoundland and since 1994 four wells have been drilled (Table 1). The play concept involved the Passive Margin Megasequence carbonate platform reservoir of Lower Ordovician age (James et al. 1989) and source rocks from a distant and coeval basinal facies (James and Stevens 1986, Fowler et al. 1995). The Taconic flexural bulge enhanced the quality of the carbonate platform reservoir through karstification and the Taconic thrusting emplaced the source rock onto the once distant platform (Figs 1 and 5). Structural traps were the result of footwall shortcuts developed when the extensional faults of the Syn-Rift Megasequence were inverted during the Acadian orogeny (Fig. 6). The seal to these traps was provided by the tight limestones and shales deposited in the Flexural Bulge and Taconic Foreland Basin megasequences. None of the earlier wells considered or tested this sequence stratigraphic and structural play concept in Western Newfoundland.

The first well, Port au Port #1 tested a small onshore structural trap downplunge of a larger offshore structure (Fig. 7). Little was known of reservoir development in the Cambro-Ordovician carbonate platform in the Passive Margin Megasequence. The only previous work had shown that the platform carbonates had porosity at Port aux Choix (Baker and Knight 1993). Good source rocks are present in the Green Point Formation of the Humber Arm Allochthon and its lateral equivalents (Fowler et al. 1995). Key risks

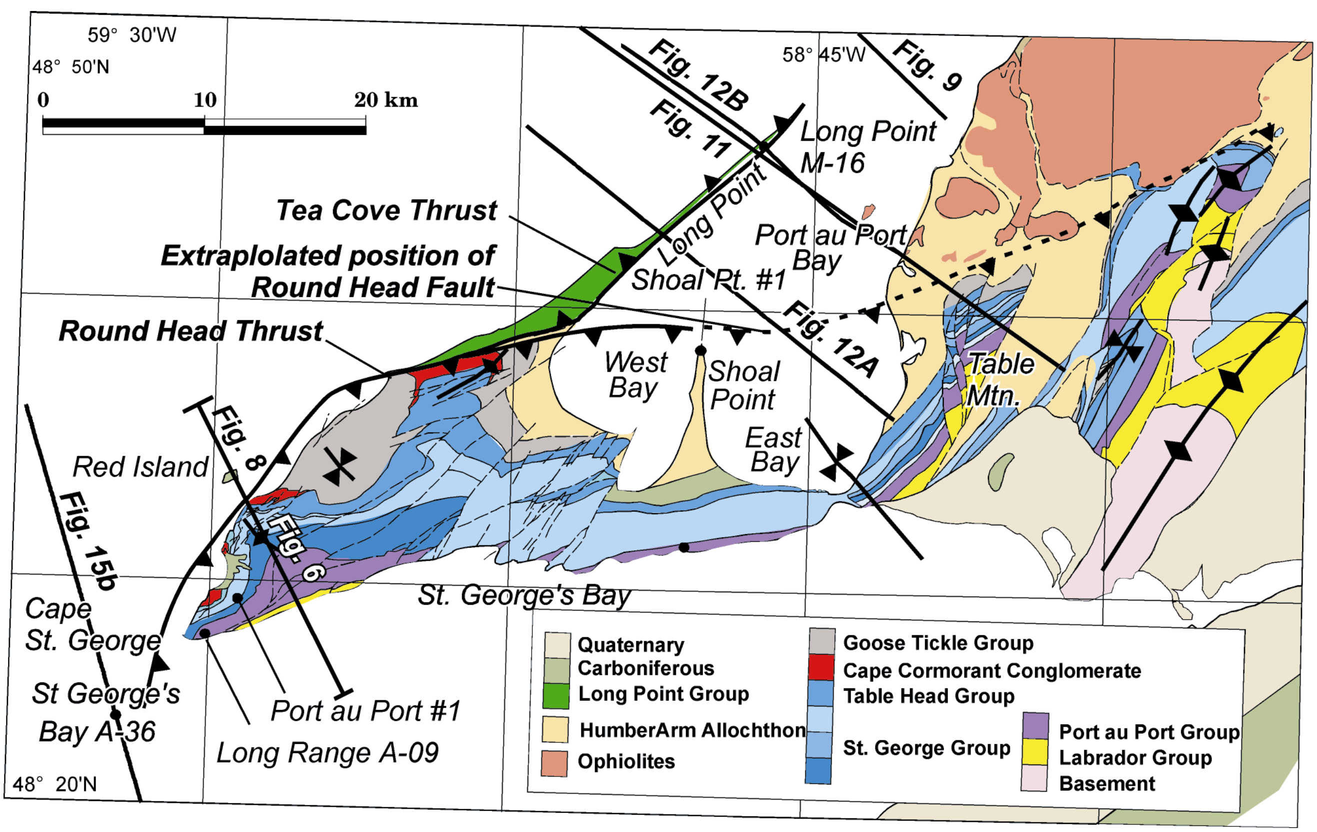

Fig. 5. Surface geology of the Port au Port peninsula and adjacent areas with locations of seismic and structural section lines. Based on data from Williams (1985), Stockmal and Waldron (1993), Palmer (1995).

TABLE 1: West Newfoundland Well Data Summary 1994-1997

Name Well Status	Location	Spud Date RR Date	KB m TD m	Tests	Cores
Hunt PCP Port au Port #1 Susp. Potential Oil Well	5372856 N 335490 E	Sept 18, 1994 June 10, 1995	220.7 m 4699 m	Test 1 Watts Bight Fm. 3916.1-3950.7m 1500-4000 bbls fm. water/d @40 Mpa Test 2 Aguathuna Fm. 3515.0-3559.5m 500-1200bbls fm. water/d @33 Mpa) Test 3 Aguathuna Fm. 3471.7-3476.2m 400-1750 bbls oil/d, wtr cut 25% @25 Mpa Test 4 Aguathuna Fm. 3459.2-3462.2m 500-2400 bbls oil/d, wtr cut 22% @25Mpa Prod. Test Aguathuna Fm 3459.2 - 3462.2 m 800-1000 bbls oil/d, water cut 35%	None
Hunt PCP Mobil Long Point M-16 Plugged & aband.	5402657 N 368161 E	Sept 10, 1995 Jan 18, 1996	22.6 m 3810 m	None	3108.96-3112m Goose Tickle or Black Cove Fm
Hunt PCP St George Bay A-36 Plugged & aband.,	5365153 N 327971 E	May 15, 1996 July 21, 1996	39.9 m 3240 m	None	#1 2040.6–2049.8m Aguathuna Fm #2 2422.9–2438.1m
Talisman et al. Long Range A-09 Plugged & aband.	5370511 N 333472 E	Feb 24, 1996 June 26, 1996	54.1 m 3685 m	Test 1 Catoche Fm. 3436.0-3461.0m 398m Gas cut Fm. H2O. Packer seat failed Test 2 Aguathuna Fm. 3308.5-3327.0m Misrun Test 3 Aguathuna Fm. 3308.5-3327.0m No flow or recovery Test 4 Catoche Fm. 3436.0-3461.0m	#1 3353.0-3461.0m Catoche Fm #2 3453.6-3462.6m Catoche Fm

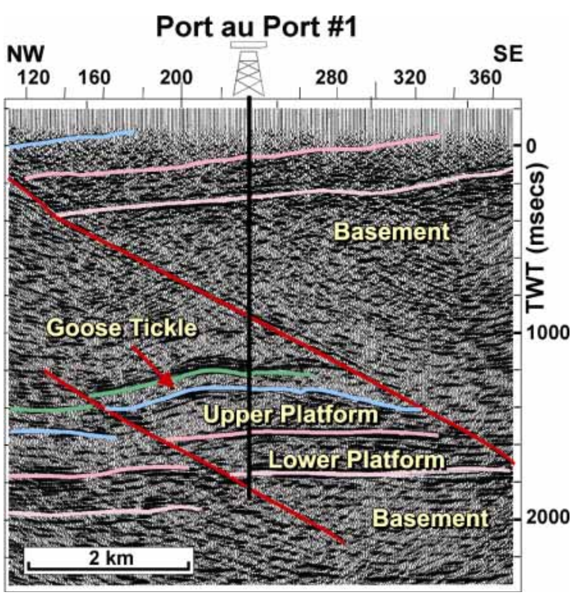

Fig. 6. Seismic line HOC-TER-CAH-93-5 showing the structure tested by the Port au Port #1 well. Line location Fig. 5. Green, base Lourdes Formation; Blue, top Table Point Formation; Orange, Campbells Member, Petit Jardin Formation; Pink, top Basement

were the maturity of the source rocks in the Port au Port area and the migration model required to move any generated hydrocarbons down through the basal thrust into the reservoir section. Work by Williams et al. (1998) suggests that the source rocks are marginally mature on the north shore of Port au Port Peninsula (Fig. 5). Beneath Port au Port Bay, where the Taconic allochthon is thicker the source rocks would be more deeply buried and in the oil window. The displacement of the Round Head Thrust is thought to decrease to the north-east (Fig. 5). There, portions of the Taconic Allochthon, including the source rocks, are juxtaposed against the reservoir units across the fault. Migration was thus considered to be across the fault into a carrier bed and southwards into structures that lay in the footwall of the Round Head Thrust.

STRUCTURAL MODELS OF HYDROCARBON

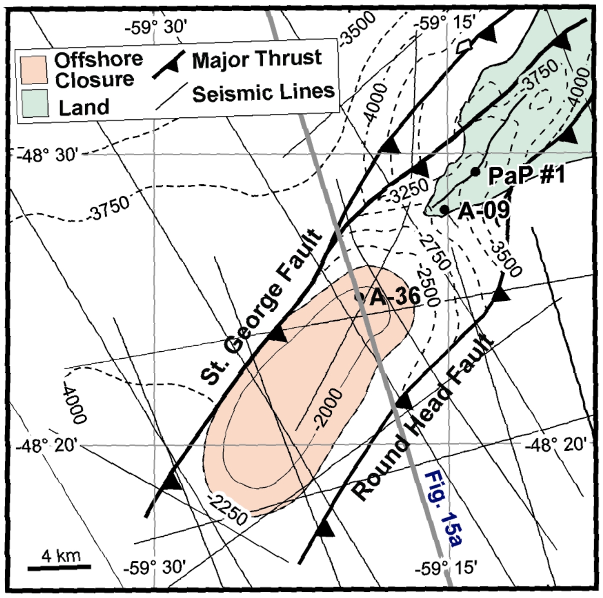

Fig. 7. Depth structure map on the top of the Table Point Formation of the SW Port au Port Peninsula and offshore areas; contours are in metres subsea. The map shows the positions of the wells drilled on the mapped closures.

TRAPS IN THE HUMBER ZONE

Structural Model of the Port au Port area

The current model of the Port au Port area has been developed by Waldron and Stockmal (1991), Waldron et al. (1993) and Stockmal and Waldron (1993). On Long Point the Long Point Group dips north-west (Fig. 5) but gradually becomes horizontal to the north-west; this monoclinal geometry has been interpreted by Waldron and Stockmal (1991) as the roof sequence of a triangle zone to which the Tea Cove thrust is the roof. The initial interpretation of the triangle zone was that it was due to thin-skinned thrust repetition of the Cambro-Ordovician passive margin clastics and carbonates (Stockmal and Waldron 1990). A later model suggested that the triangle zone was due to a blind, thin-skinned slice of Grenville basement and cover rocks thrust westward on a Goose Tickle detachment. In this model, the Round Head Thrust was interpreted as a localized thrust reactivation of an originally extensional, basement involved fault, (Stockmal and Waldron 1993, fig 4). A later model suggests that the fault is a thick-skinned inverted extensional fault and emerges at surface as the Round Head thrust which developed later than and offset

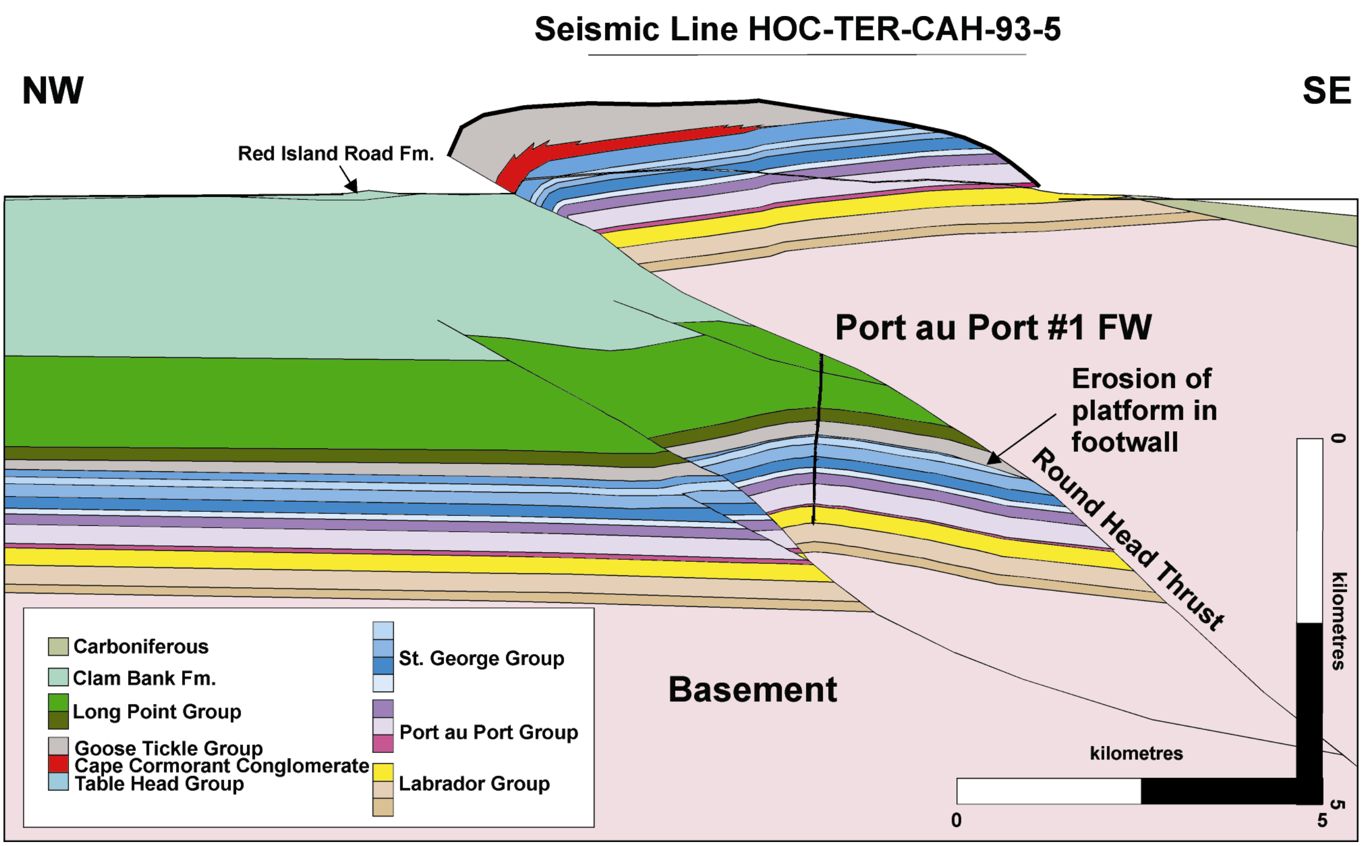

Fig. 8. Structural cross-section through the Port au Port #1 well based on surface geology, seismic data and dip and formation data from the well.

the triangle zone (Stockmal et al. 1998). The Port au Port #1 well essentially demonstrates that the revised model of the Round Head Thrust is correct. The well penetrated 615m of granitic Grenville basement before crossing the Round Head Thrust (Fig. 8). In the footwall of the Round Head Thrust a minor imbricate repeated the upper Winterhouse Formation (Fig. 8). From both a stratigraphic and structural perspective however, the most significant thickness and facies changes occurred in the Flexural Bulge Megasequence. As has been discussed above the Port au Port #1 well provides the first direct evidence for the earlier extensional history of the Round Head Fault (Fig. 4) postulated by Stenzel et al. (1990) and Stockmal et al. (1998).

The Triangle Zone

The Long Point M-16 well was directionally drilled from the northern tip of Long Point (Fig. 5) eastwards beneath Port au Port Bay. The well spudded in the NW dipping Lourdes Formation in the hangingwall of the Tea Cove Thrust (Stockmal and Waldron 1993). The nearest predrill seismic line to the well (CHA 92-1B, Fig. 9) shows the north-west dipping Long Point Group and younger strata and other sub-horizontal reflectors of the Cambro-Ordovician passive margin. Within the triangle zone a number of south-east dipping reflectors can be seen, which could be thin-skinned imbricates of the Humber Arm Allochthon and/or the Cambro-Ordovician platform. An alternative model invokes the combination of thin-skinned deformation in the Humber Arm Allochthon and thick-skinned compressional faults that elevated the Cambro-Ordovician platform and basement. The thick-skinned faults probably originated as extensional faults created during the Syn-rift and/or Flexural Bulge megasequences.

The well penetrated a series of folds and imbricate thrusts within the Humber Arm Allochthon beneath the Tea Cove Thrust. The structural interpretation is based on the biostratigraphic data and dip and image data derived from the Formation Micro-scanner (FMS) log. The FMS log was subdivided into "image facies" of distinctive appearance. The first was conglomeratic with clasts of varying size suspended in a matrix (Fig. 10a); these were interpreted as debris flows perhaps correlative with the Cow Head Group. The second was a thin banded multi-layer interpreted as ribbon limestones occurring in deep marine shales and perhaps correlative with the Cooks Brook or Middle Arm Point formations (Fig. 10b). The final "image facies" were massive, low resistivity, well-bedded units which could either be thicker sands or limestones. Distinctive sequences of "image facies" were correlated using the biostratigraphic data. These showed a general downward increase in age in the well-bore and some significant downhole shifts to younger ages implying either fold or thrust repetition of the sequences (Fig. 11). The changes to younger ages together with dip data were used to locate candidate faults and fold axes within the Humber Arm Allochthon.

The basal thrust of the Humber Arm Allochthon is visible as a shear zone on the Formation Micro-scanner image log; beneath the basal thrust is the Goose Tickle Group. The Flexural Bulge and Passive Margin megasequences strata dip at 15^{o}NW and are significantly elevated above their regional elevations in the undeformed area north-west of the triangle zone. This structure is interpreted as a basement involved compressional fault, perhaps similar in origin to the Round Head Thrust (Fig. 11). The Table Point Formation is 60 m thick in the well suggesting a location off the crest of a fault footwall where the formation should be much thinner (c.f. Port au Port #1). Thus the Long Point M-16 well demonstrates that the Triangle Zone described by Stockmal and Waldron (1990) and Waldron and Stockmal (1991) is the result of imbrication in the Humber

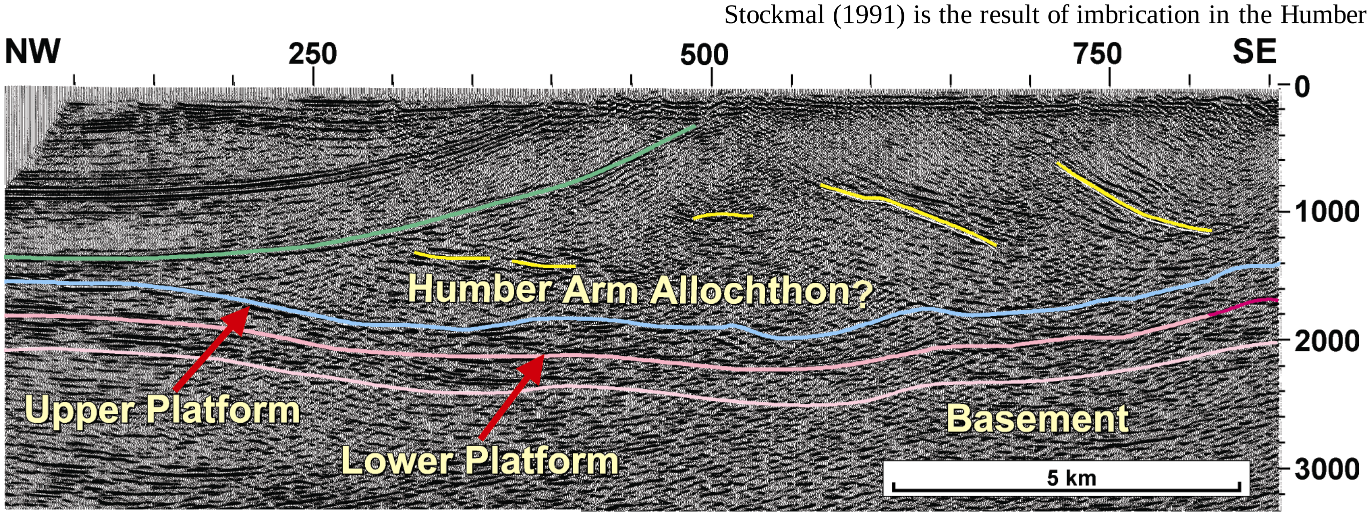

Fig.9. Seismic lineCHA-92-1B, for location see Fig. 5 and for legend see Fig.6.

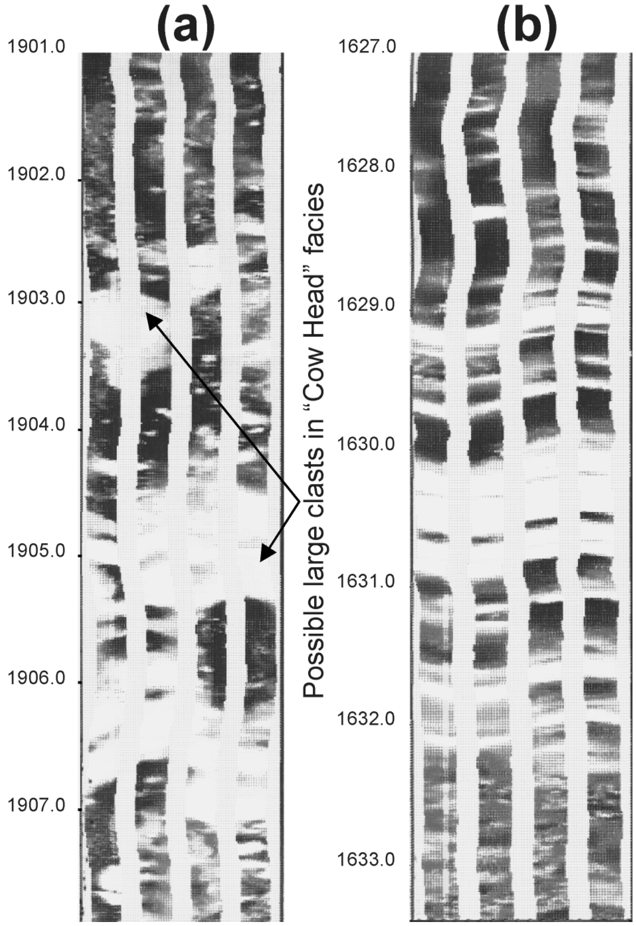

Fig. 10. FMS "image facies" from the Long Point M-16 well; (a) clasts in a conglomeratic interval; (b) ribbon limestones in a shale dominated section.

Arm Allochthon combined with thick-skinned compressional faulting.

The Round Head Thrust

Stockmal and Waldron (1993) have suggested that the present day trace of the Round Head Thrust could be inferred from the enveloping surface of the autochthonous and para-autochthonous strata. They proposed that the Round Head Thrust swung eastward after crossing the Port au Port peninsula and maintained an ENE trend through the northern end of Table Mountain (Fig. 5). Seismic lines acquired allow a fundamental re-interpretation of the Round Head Thrust in Port au Port Bay which has an extensional offset which increases to the north (Fig. 12). A depth structure map on the top of the carbonate platform shows that the footwall cut-off against the Round Head Fault is a relatively straight line (Fig. 13). The hangingwall cut-off of the top platform against the Round Head Thrust trends NNE-SSW off the western coast of the Port au Port Peninsula before swinging around eastwards and cutting ENE-WSW across the peninsula (Fig. 5). This swing in trend is interpreted as a displacement gradient. As the fault loses displacement the hangingwall cut-off would track eastwards down the fault surface causing the hangingwall cut-off to display a marked change in trend in map view. In West Bay, the Round Head Thrust rapidly loses displacement and passes through a null point just to the SW of the tip of Shoal Point (Fig. 13).

Outcrops of the carbonate platform on the Port au Port peninsula fits this model. The units in the hangingwall of the Round Head Thrust dip NW - N and change trend to

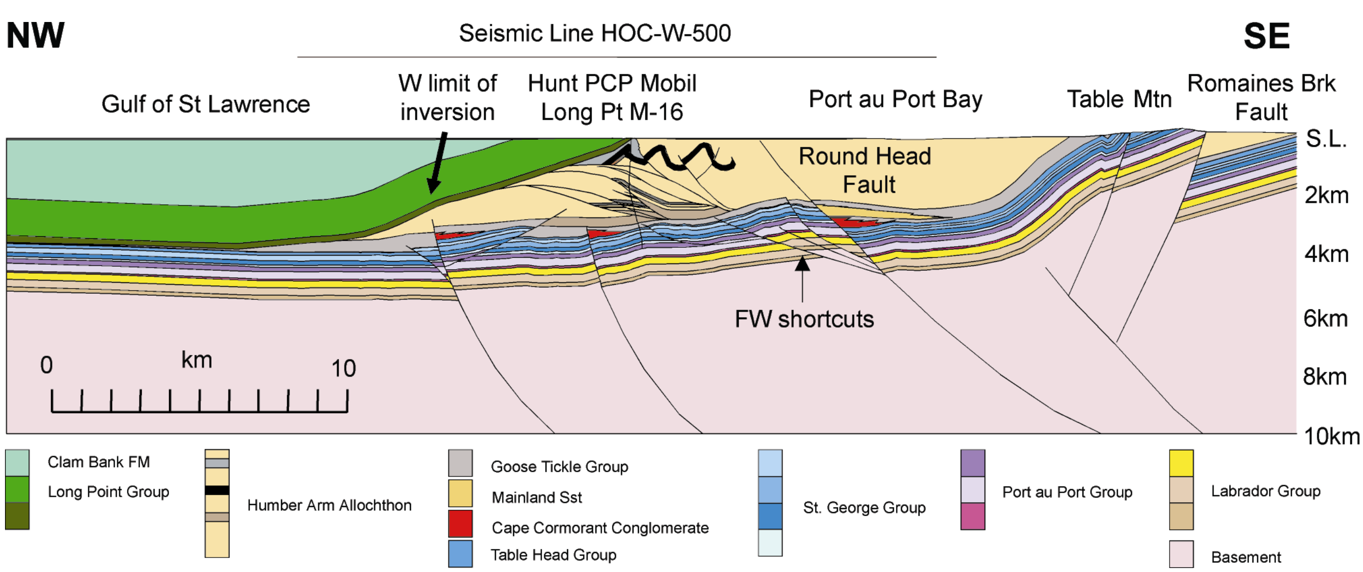

Fig. 11. Structural cross-section through the Long Point M-16 well based on well data, seismic and surface geology. Line location on Fig. 5.

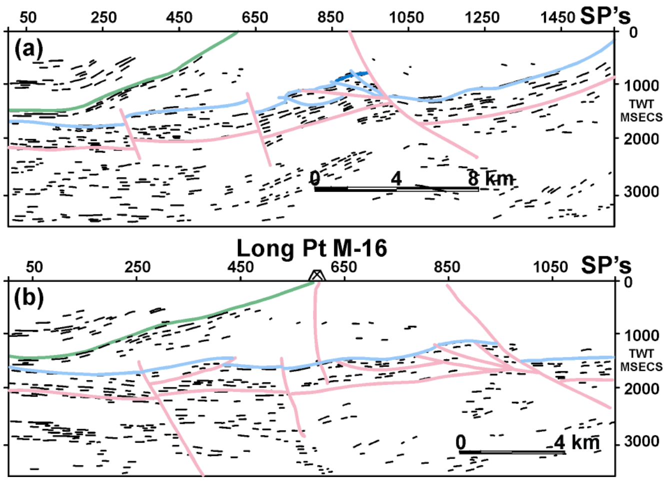

Fig. 12. Line drawings of high amplitude reflectors on seismic lines (a) HOC-W-300 and (b) HOC-W-500 from Port au Port Bay, locations on Fig. 5, legend on Fig. 6.

cut across the peninsula (Fig. 5). When the carbonate platform outcrop is included as a constraint on the depth-structure map no major breaks occur in the hangingwall from Port au Port Bay onto the peninsula and the contours are compatible with the observed dips on the peninsula (Williams 1985).

When the additional data provided by the wells and seismic profiles is integrated with the surface geology it strongly suggests that the Round Head Thrust is an extensional fault in Port au Port Bay that becomes progressively more inverted as it is traced southwards onto Port au Port Peninsula. If this is the case then local accumulations of the Cape Cormorant conglomerate are still present at depth along the fault. Compressional footwall shortcuts are still present north of the null point on the fault despite the Round Head Thrust being in net extension at the top of the Table Point (Fig. 12), indicating that the fault has suffered some inversion. An alternative model for the seismic data in Port au Port Bay is to invoke a change in thrust vergence northwards and to interpret the fault on the seismic as an east vergent thrust fault.

Regional Structural Style

To illustrate regional structural style, a series of cross-sections have been constructed (Fig.1). These sections have been interpreted by using the new maps compiled by the Newfoundland Department of Mines and Energy (Knight, 1991, 1994) and available seismic data. The interpretation of the structural style has been influenced by the detailed data available in the Port au Port area as a result of the drilling and intensive seismic data acquisition. The sections illustrate a model that involves Taconic em-

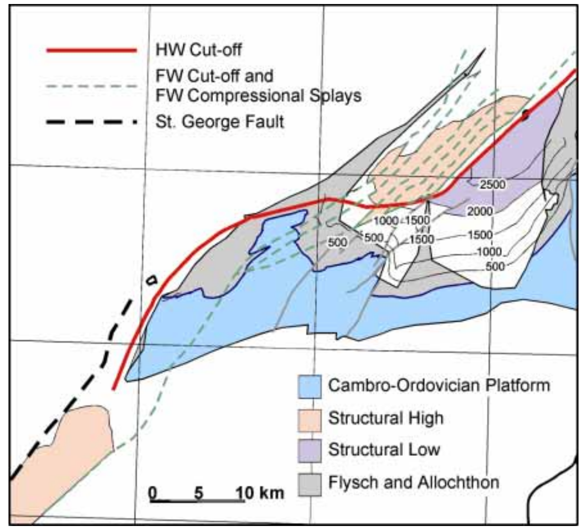

Fig. 13. Depth structure map on the top of the Table Point Formation based on seismic data, well data and surface geology; contours are in metres subsea. The Round Head Fault is in net extension where the hangingwall cut-off (HWC) lies to the SE of the footwall cut-off (FWC) and in net compression where the HWC lies to the NW of the FWC.

placement of the Humber Arm Allochthon probably as far west as the present day coast (Fig. 14). This was followed by thin-skinned Salinic deformation of the autochthonous platform to the east during the Silurian. Acadian thick-skinned deformation elevated basement to the east causing gravitational gliding of the Humber Arm Allochthon and the overlying ophiolites into their present location (Knight and Cawood 1991, Fig.14). The triangle zone exposed at Long Point may be the contractional toe of this system. The westward migration of the thick-skinned Acadian deformation subsequently faulted and modified the triangle zone (Fig. 14).

St. George's Bay A-36 Well Section

The A-36 well drilled the offshore extension of the footwall shortcut developed beneath the Round Head Thrust and tested by the Port au Port #1 well (Figs 7, 15a). The geology is complicated offshore by the Carboniferous St. George Bay Basin and which unconformably truncates the Round Head Thrust (Fig. 15a). To the south the footwall shortcut anticline is poorly imaged on seismic data. The top of the platform was 1200m higher than in Port au Port #1 but the Table Point Formation was 70m thick indicating that the well was not located at the crest of a Flexural Bulge megasequence paleo high. The thickness of the Table Point Formation suggests that the footwall cut-off is on the south-east limb of the footwall shortcut anticline. This cross-section illustrates the typical trap geometry tested to-date by drilling (Fig. 15a).