Petroleum Exploration Enhancement Program

Report: Evolution of the Appalachian foreland basin and thrust front, western Newfoundland (2010-2012).

Authors: Shawna White & John Waldron, Department of Earth & Atmospheric Sciences, 1-26 ESB, University of Alberta, Edmonton AB.

1 Introduction

Structures associated with the Appalachian deformation front in Western Newfoundland have been of recent interest due to the discovery of hydrocarbons at the Port au Port #1 ("Garden Hill") well. Exploration interest associated with this discovery has led to the availability of offshore seismic data, allowing for imaging of the front and the possibility of other oil plays associated with structures in the vicinity of the deformation front.

The Appalachian orogen is an extensive belt of Mesoproterozoic to Paleozoic rocks along the eastern margin of North America. It extends from Alabama, to the south, to its northern-most limits in Newfoundland, where vast amounts of exposure, and more recently, the availability of seismic reflection data, offer one of the best opportunities to study and understand the orogen's history. The limit of Appalachian deformation bounds the westernmost margin of the orogen and, in Newfoundland, lies offshore below the Gulf of St. Lawrence (Figure 2).

The following report details the field and lab work carried out during 2010-2012, as part of the PhD thesis of S.E White. During this time we aimed to combine surficial mapping, onshore and offshore seismic data along with detrital zircon U/Pb age data in order to form a better understanding of the geological history and petroleum potential of the deformation front of the Newfoundland Appalachians.

2 Geology

This report focuses on the geology of the western portion of the Port au Port Peninsula, and offshore regions below the Gulf of St. Lawrence (Figure 2). This area lies at the structural front, which marks the boundary between the Appalachian foreland basin and the Humber Zone, the westernmost tectonic zone of the Newfoundland Appalachians (Figure 1). The region to the east of the deformation front (Humber Zone) is characterized by a Cambrian-Ordovician passive margin succession, which has been deposited on rifted, crystalline Mesoproterozoic basement (Figure 2). West of the Humber Zone are sedimentary rocks of the Middle Ordovician to Early Devonian foreland basins. Rocks in the Humber Zone and at the structural front have been deformed during a protracted series of deformation events beginning in the Early Ordovician and lasting through to the Carboniferous (Waldron et al., 1998). In the study area, on the Port au Port Peninsula, stratigraphic relationships are well preserved (Figure 2). By studying the stratigraphy (Figure 3) and structure we hope to better understand the geologic history of the external zone and, in particular, the deformation history at the deformation front.

2.1 Stratigraphy

2.1.1 Shelf Succession

The oldest rocks within the Humber Zone are Mesoproterozoic basement units that are exposed as slices within Paleozoic metamorphic complexes in the eastern internal Humber Zone and as massifs within the western external Humber Zone. These include the Long Range Inlier, which forms the highlands of the Northern Peninsula in western Newfoundland, and the smaller Indian Head Inlier, located in the Stephenville area (Owen, 1991: Figure 2). Atop these crystalline basement rocks, an extensive rift-drift succession of Lower Cambrian to Lower Ordovician units is exposed along the length of the Humber Zone although their autochthonous versus allochthonous nature varies from south to north. This succession can be divided into three groups. The oldest is the dominantly clastic, Lower Cambrian Labrador Group, deposited as a result of Neoproterozoic rifting (e.g. Cawood et al., 2001) and subsequent development of Laurentia's Iapetan margin. The Labrador Group is overlain by thinly bedded carbonates of the Middle to Late Cambrian Port au Port Group, interpreted as representing a relatively high energy, narrow shelf (Chow and James, 1987). The Early Ordovician St. George Group forms the top of the shelf succession, consisting of massive, thick-bedded limestone and dolostones, interpreted to represent an extensive, lower-energy shelf environment (Pratt and James, 1986).

2.1.2 Foreland Basin Successions

During various stages of orogenesis in the Newfoundland Appalachians, sediments were shed from the advancing orogen into a developing foreland basin (Figure 1). Within the shelf successions, the onset of tectonic activity is recorded by the St. George unconformity (Knight et al., 1991), interpreted to record the passage of a lithospheric flexural bulge formed during loading by Taconian allochthons (Jacobi, 1981). The overlying Table Point Formation (Figure 3) is therefore the basal unit of the foreland basin succession, but because of its similar facies is informally included as part of the "platform succession". Depending on location, various units may lie above the Table Point Formation. On the west coast of the Port au Port Peninsula, it is overlain by conglomerate, calcarenite and shale of the Cape Cormorant Formation. Where the Cape Cormorant Formation is absent, Table Point rocks are overlain by interbedded limestone and shale of the Table Cove Formation and black shale of the Black Cove Formation. The progression of these units demonstrates a deepening of the basin.

The transition to orogen-derived clastic sediments is recorded by Ordovician turbiditic sandstone of the Goose Tickle Group. Petrographic analysis of the Goose Tickle Group suggests derivation from both the immediately surrounding rock units (Quinn, 1992) and ophiolitic rocks in the Humber Arm Allochthon (Stevens, 1970).

Younger foreland basin units are only exposed along the western coast of the Port au Port Peninsula (Rodgers, 1965), where Goose Tickle rocks are interpreted to be overlain by the shallow marine, fossiliferous Lourdes Limestone, the basal unit of the Late Ordovician Long Point Group. Deep-water siliciclastics of the Winterhouse Formation gradationally overlie the Lourdes Formation. These thin-to medium-bedded, fine-grained sandstones, interpreted to represent a storm-dominated shelf (Quinn et al., 1999) are in turn gradationally overlain by redbeds of the Misty Point Formation, characterized by medium-to-coarse grained, red sandstone interpreted to represent a marginal marine to terrestrial setting (Quinn et al., 1999). The Late Ordovician age for the Long Point Group is significant, in that there is no documented orogenic event in the Newfoundland Appalachians that can be directly correlated with foreland basin development at this time.

The Late Silurian to Early Devonian Clam Bank Formation (Burden et al., 2002) is interpreted to overlie rocks of the Long Point Group; however, nowhere on-land is this stratigraphic contact preserved. The lowest portion of the Clam Bank Formation is a mixed marine/terrestrial, carbonate/clastic unit; an unconformity above this lower portion is marked by a transition to a dominantly terrestrial environment (Quinn, 1994). Clast-supported conglomerates and sandstones of the Red Island Road Formation overlie the Clam Bank Formation (Figure 3). This unique formation is exposed only on Red Island.

2.2 Previous Structural Work

Offshore of Port au Port, 2D seismic profiles image a thin-skinned tectonic wedge (Stockmal and Waldron, 1990; Waldron and Stockmal, 1991), which is interpreted to be occupied by rocks of the Humber Arm Allochthon together with probable Goose Tickle Group Rocks (Stockmal et al., 1998: Figures 2, 5b and 5c). The wedge is bounded at the top by the Tea Cove thrust, an east-vergent back-thrust formed due to westward emplacement of the wedge. This fault can be traced onshore through Tea Cove, Port au Port Peninsula (Stockmal and Waldron, 1990: Figure 2), and represents the leading edge of deformation in the Newfoundland Appalachians. At Tea Cove, it is observed that Late Ordovician and Early Silurian foreland basin fill overlie the tectonic wedge. Due to the parallel nature of folded reflectors above the wedge, Stockmal et al. (1998) suggested that the wedge of Humber Arm Allochthon rocks was emplaced after deposition of overlying units during the Devonian. This suggests Acadian remobilization of the Humber Arm Allochthon to its current structural position.

3 Objectives

The objectives of this project were:

1) Examine outcrop-scale structures associated with the Round Head thrust, Port au Port Peninsula, to determine the transport direction and state of strain near the thrust, and its impact on fracture development.

2) Examine available seismic data, onshore and offshore, to determine the timing of thrusting along the thrust front and to produce a coherent model of thrust front evolution.

3.) Use available seismic data to determine the geometry of the foreland basins and constrain the history of tectonic loading by the orogen.

4.) Determine the nature of source regions for post-Taconic foreland successions and their relation to the Newfoundland Appalachians.

4 Methods

This project involves a combination of field mapping, seismic interpretation and detrital zircon analysis to facilitate a better understanding of the deformation front.

4.1 Field Mapping and fracture studies

A total of 2.5 months was spent collecting field data in summer 2011. Field work on the Port au Port Peninsula mainly involved the documentation of faults and folds near the deformation front (Figure 2). In particular, structures in both the footwall and hanging wall of the Round Head thrust were measured and their orientation, geometry, pervasiveness and genetic relationships were carefully documented (Figures 4a and b). These data have been combined with seismic interpretations in order to better understand the 3D structure and deformation history of the structural front; results of this work are currently being prepared for publication. Our understanding of these structures may aid in discovery of trapped hydrocarbons.

4.2 Seismic Interpretation

Since publication of seismic studies along the western coast of Newfoundland in the 90's, newer, onshore and offshore, 2D seismic reflection data have been collected. The data, shot by various companies, have since been scanned and converted into SEGY format. This large collection of data, including thousands of kilometres of 2D seismic reflection data, has been made available to this project through Leprechaun Resources (Figure 5a). and loaded into Petrel, a seismic interpretation software package.

In order to use 2D seismic reflection profiles to make interpretations regarding geologic history, seismic reflectors needed to be tied to specific geological boundaries. Due to lack of well-ties, ties were made using outcrop exposures and magnetic signatures within foreland basin sediments (e.g. Waldron et al., 2002). A regional geologic review was undertaken to aid correlation. Using profiles shot by Mobile in 1991 (Figure 5a), three distinct reflectors have been identified and correlated with specific geologic boundaries within the stratigraphic succession comprising: the top of Platform; base of the Lourdes Limestone; and base of the Clam Bank Formation (Figures 5b, 5c and 5d). All reflections demonstrate high amplitude, positive seismic signatures. Figures 5b and 5c show interpreted seismic profiles offshore of the Port au Port Peninsula.

4.3 U/Pb Detrital Zircon Provenance

Samples for detrital zircon analysis were collected during the 2011 field season on the Port au Port Peninsula from all three foreland basin successions. These samples were chosen based on lithology and age control. Medium-grained sandstones were preferable, due to the likelihood of choosing a zircon-rich sample and samples within horizons with graptolite and/or faunal assemblages were chosen in order to constrain depositional age. Stratigraphic sample locations are depicted on Figure 3. In total, eight samples were shipped to Dalhousie University for grain separation. Grain separates from samples of the Red Island Road Formation and Winterhouse Formation have been examined under optical microscope and mounted; in order to avoid bias, grains were not selected based on colour, morphology or alteration. Grain mounts were made for these two samples and prior to Laser Ablation ICP-MS, were imaged using the scanning electron microscope, and x-ray elemental maps of zirconium were made. These procedures ensure proper selection of ablation sites on grains. Samples were analysed at the

University of Alberta's Radiogenic Isotope Facility using a Nu Instruments Nu Plasma MC-ICP mass spectrometer coupled with a New Wave Research UP213 laser ablation system. U/Pb Isotopic ratios and detrital zircon ages will be determined. The same techniques will be used for other collected samples that were separated. In addition, selected rhyolite cobbles were analysed by Thermal Ionization Mass Spectrometry (TIMS) at Memorial University of Newfoundland with the cooperation of Dr. G. Dunning.

5 Results

The geometry of the reflector configuration has important implications regarding the geologic history at the Appalachian Deformation front and some initial observations and interpretations are made.

5.1 Thick-skinned faults

Deep-seated basement faults are observed in seismic profiles of the foreland basin, but only offset platform and basement rocks, and do not penetrate into the foreland basin sediments. The majority of these faults offset the platform with normal displacement, and are interpreted to represent normal faults generated during Taconian loading of the platform, and may have been active since Neoproterozoic rifting and opening of the Iapetus. Some of the deep basement involved faults show thrust displacement, suggesting reactivation of normal faults, maybe during later Early Devonian deformation (during the Acadian Orogeny). These faults appear to have a dominantly northwest strike. In general faults are not observed to offset the foreland basin stratigraphy with any significant displacement, and beyond the structural front (Tea Cove thrust) the reflectors are laterally continuous, suggesting this is the limit of Appalachian deformation.

5.2 Tea-cove thrust

Offshore of the Port au Port Peninsula, the reflectors overlying the Tea Cove Thrust are parallel. These reflectors are within sediments of the Late Ordovician Long Point Group and Early Devonian Clam Bank and Red Island Road formations. This has led previous authors to suggest that the tectonic wedge was inserted after deposition of these units, during the Early Devonian Acadian orogeny (Stockmal and Waldron, 1990: Figure 5b). Further north however, offshore of Bonne Bay, the reflectors demonstrate a thinning above the wedge (Figure 5c), suggesting that the insertion of the wedge to the north was most likely a syn-depositional event, beginning in the Late Ordovician, during deposition of the Long Point Group. These observations lead us to conclude that movement along the structural front was diachronous, beginning earlier, in the Late Ordovician, to the north, and later (Early Devonian) to the south. Long wavelength folds are also observed within the foreland basin sediments in the hanging wall of the Tea Cove Thrust (Figure 5c). These folds may have implications for petroleum exploration, where structural domes, if they have four way closure, could be potential petroleum traps.

The stratigraphic position of the Tea Cove thrust is not constant along strike of the fault. In figure 5b, the thrust follows the base of the Lourdes Limestone; however figure 5c displays it at a stratigraphically lower level, within presumed the Goose Tickle Group. A similar scenario is apparent in profiles along the front, suggesting a lateral ramp geometry along the length of the thrust front length, cutting down through stratigraphy towards the north.

5.3 Lateral variation and provenance of foreland basin stratas

The high amplitude, peak which represents the Lourdes limestone becomes more difficult to trace to the north, which may suggest one of two things: 1.) The Lourdes Limestone may change physical characteristics to the north, or perhaps the Lourdes Limestone may not represent the base of the Long Point Group in the North.

Thickness variations within foreland basin successions are also observed. There is a dramatic thickening of the Long Point Group to the south, along strike of the basin axis. This thickening corresponds with a thinning of the Goose Tickle Group to the south (Figure 5d). The Late Ordovician age of the Long Point Group does not correspond directly with the timing of any orogenic event witnessed in the Newfoundland Appalachians, and therefore the tectonic significance of the subsidence recorded by this package has been speculative. The southward thickening that we observe, however, may be related to a loading event in more southern regions of the Canadian Appalachians. Further analysis of seismic sections and ongoing provenance work may help to shed light on source regions for the Long Point Group.

The Late Silurian though Early Devonian age of the youngest foreland succession (Clam Bank -- Red Island Road succession) can be correlated with the Late Silurian to early Devonian Acadian orogenic event in the Newfoundland Appalachians suggesting an easterly source for the unit; however local sources for felsic volcanic clasts within the Red Island Road Formation are unknown (Quinn et al., 2004). A sample of the rhyolite clasts was collected during the 2011 field season and was dated by G. Dunning (Memorial University, personal communication 2012). Two ages, overlapping concordia, were obtained, based on separate analyses, at 420.3 and 421 Ma, (each about +/-2.) The weighted average of the two ages, interpreted as the age of the cobble,is 421 +/-1.3 Ma (95% confidence interval, MSWD= 0.5). A possible source region in Newfoundaland is the LaPoile Group. However, an alternative possibility is the Aspy terrane in

Nova Scotia, as these units was deposited before Carboniferous strike slip faulting which may have accounted for up to 250 km of dextral strike slip (Hibbard and Waldron 2009). Restoring this later deformation would place the Aspy terrane adjacent to the current position of the Indian Head Inlier.

6. Conclusions and future work

Results to date have resulted in improved understanding of the Appalachian deformation front and foreland basins in western Newfoundland, with implications for the provenance, stratigraphy and structure of rocks that form potential conventional and unconventional reservoirs in western Newfoundland. These results are currently being prepared for publication as part of the PhD thesis work of S.E. White, in combination with work undertaken during the 2012 and 2013 field seasons, which focused on the on-land thrust front on the Northern Peninsula.

Acknowledgments

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Figure 1: Tectonic Zonation of the Canadian Appalachians after Hibbard et al (2006).

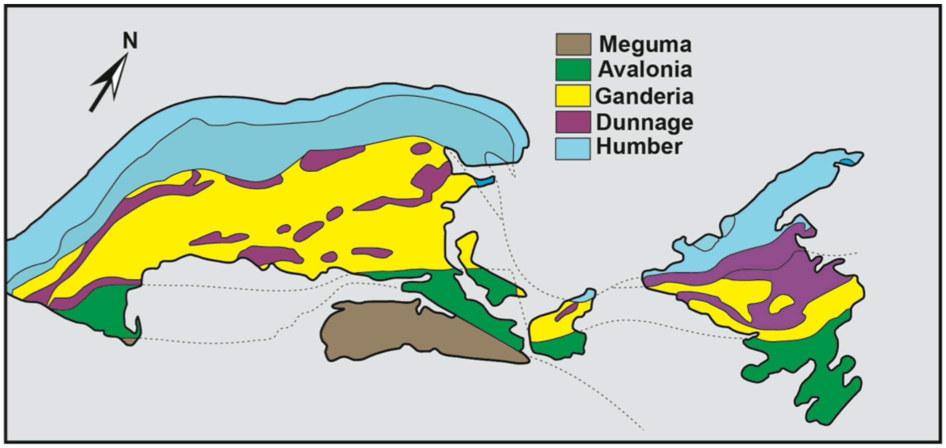

Figure 2: Geological map of the Humber Zone of the Newfoundland Appalachians. The Tea Cove Thrust corresponds to the structural front of the Appalachians in Newfoundland.

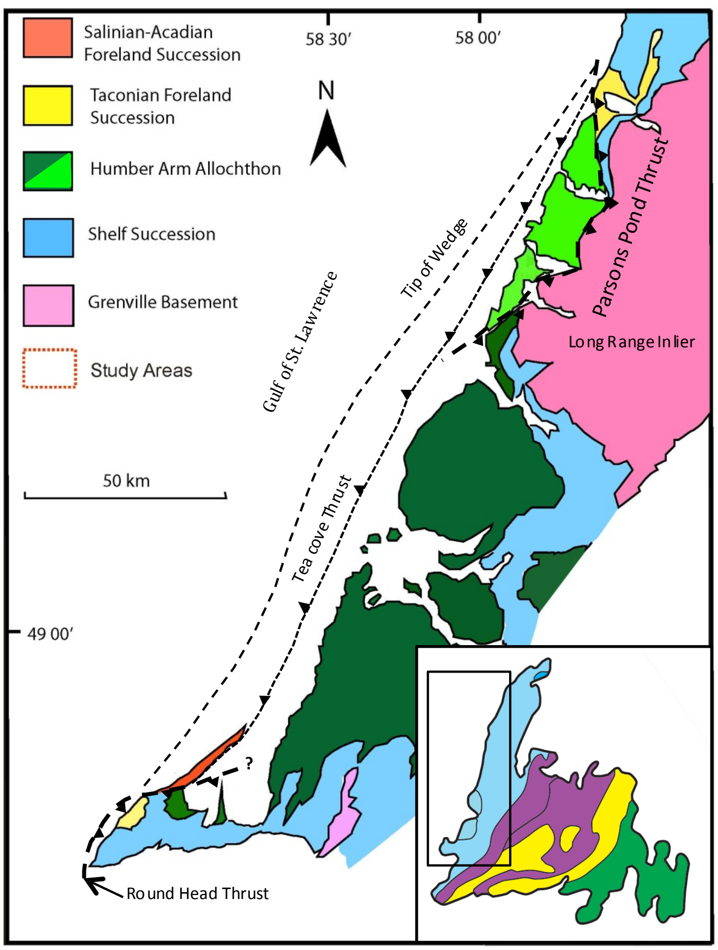

Figure 3: Generalized stratigraphy in the Humber Zone, western Newfoundland (Modified from Stockmal et al., 1998). Positions and colours of reflectors correlate with prominent reflectors in seismic profiles. Red stars indicate the approximate stratigraphic positions of detrital zircon samples.

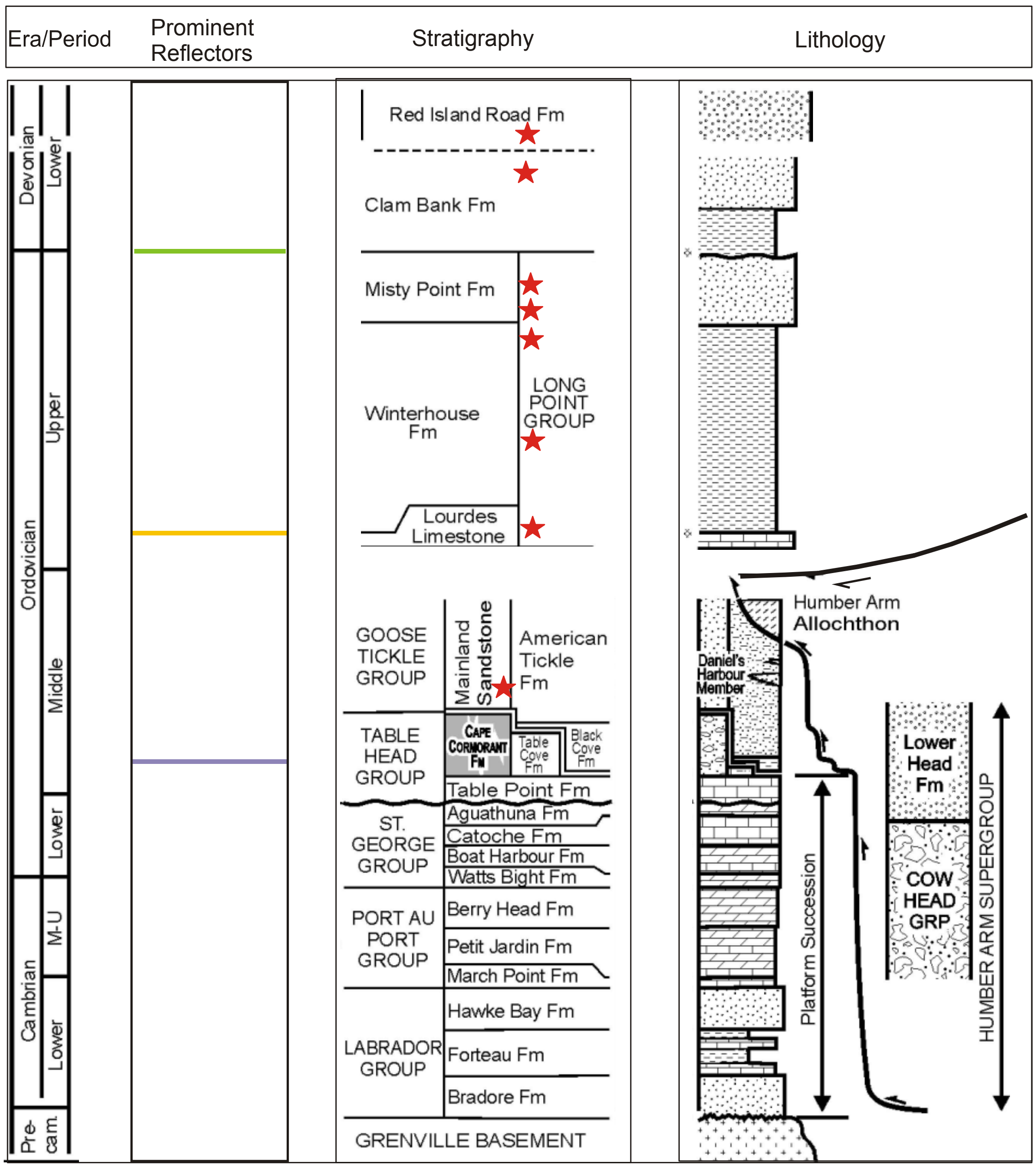

Figure 4 a,b: Stereonets showing structures in the vicinity of the Round Head Thrust (RHT) on Port au Port Peninsula. 4a, shows northwest dipping normal faults at Three Rock Point which are pervasive in the area. This region is interpreted to sit in the direct footwall of the RHT. Figure 4b shows north- and south-striking conjugate thrust faults on long point, in the footwall of the RHT, but far removed from the interpreted position. These faults are most likely related to thrusting on the east vergent, south striking, Tea Cove thrust. 4c Locations on map of the Port au Port Peninsula showing the major structures based on Waldron & Stockmal (1991) and Knight (2007).

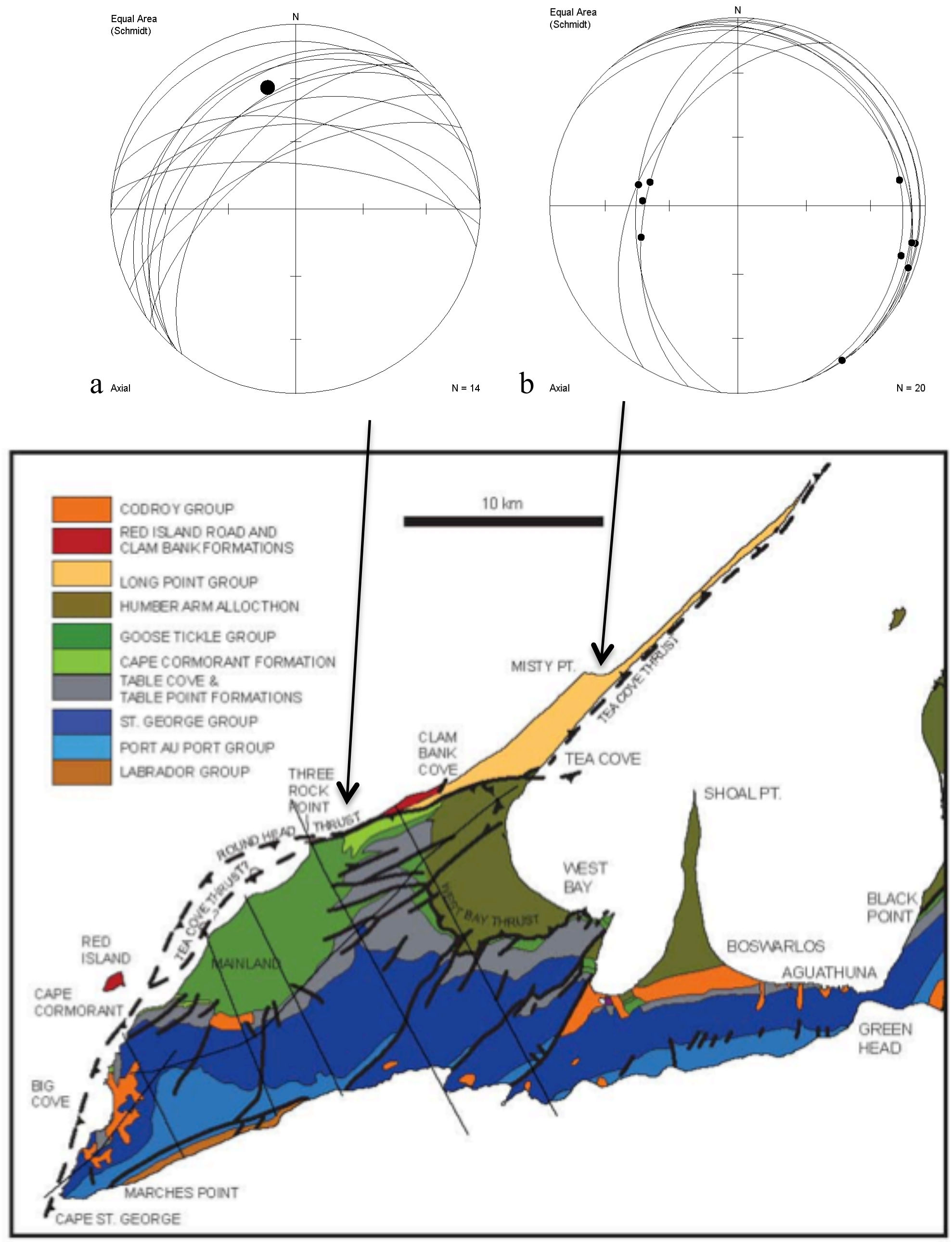

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Figure 5a: Map displaying seismic line locations along the west coast of Newfoundland.

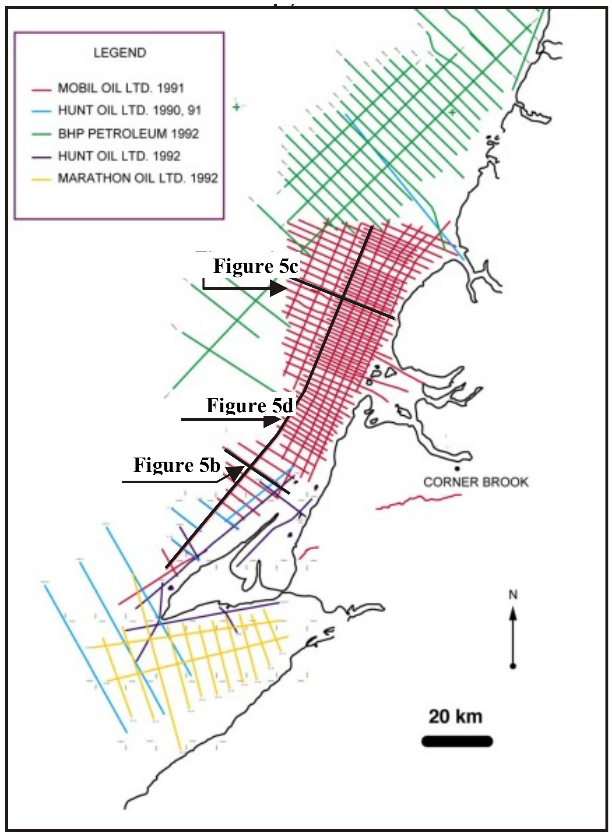

Figure 5b: Seismic profile showing tectonic wedge inserted into Goose Tickle Group rocks. HAA = Humber Arm Allochthon; GT = Goose Tickle Gp.; TCT = Tea Cove Thrust. Vertical exaggeration ~ 4x. See text for details.

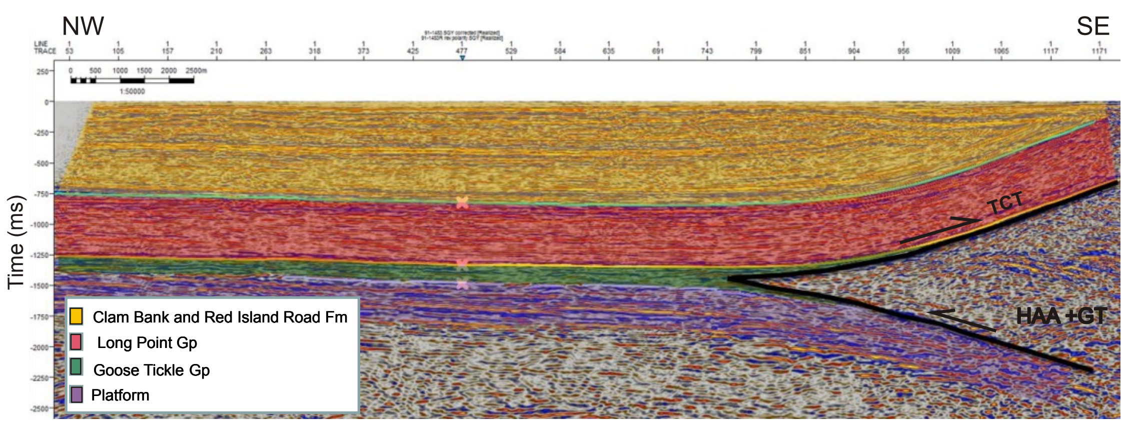

Figure 5c: Seismic profile showing tectonic wedge being inserted into Goose Tickle Rocks. Note thickening of Goose Tickle Group and thinning of Long Point Group stratigraphy. Vertical exaggeration ~ 4x.

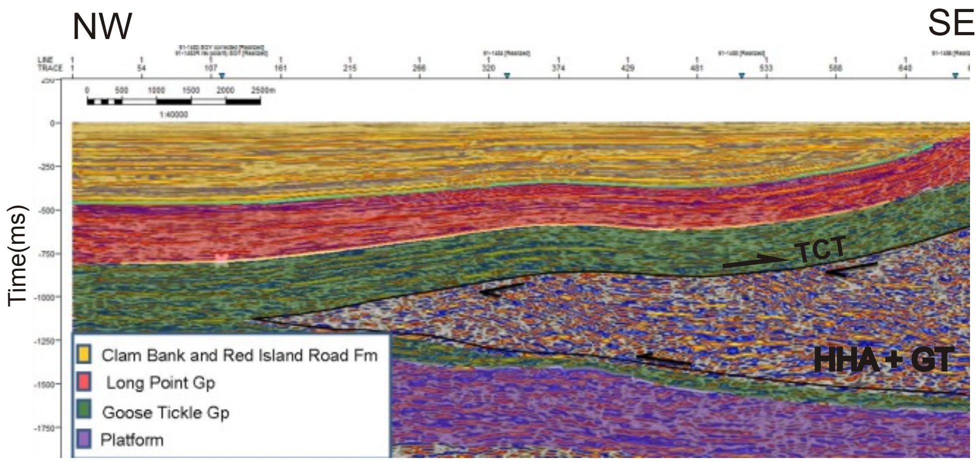

Figure 5d. Seismic profile along approximate strike line of foreland basin stratigraphy. No vertical exaggeration. Note thickening of Long Point Group above yellow reflector (base of Lourdes Limestone) and below green reflector (Base of Clam Bank Formation). Purple reflector is top of platform.