

CONJUGATE MARGINS CONFERENCE 2018

Celebrating 10 years of the CMC: Pushing the Boundaries of Knowledge



Short Course 2

Salt Tectonics Field Seminar: Diapirs and Associated Deformation

Cape Breton Island, Nova Scotia, August 22-25, 2018

ISBN: 0-9810595-12



CONJUGATE MARGINS CONFERENCE 2018

Celebrating 10 years of the CMC: Pushing the Boundaries of Knowledge

Halifax, Nova Scotia, Canada | 19-22 August 2018 | www.conjugatemargins.com

Conjugate Margins Conference Official Field Trip

22-25 August 2018

Salt Tectonics Field Seminar: Diapirs and Associated Deformation

FIELD TRIP GUIDE

Cape Breton, Nova Scotia



Field Trip Leader: Ian Davison



CONJUGATE MARGINS CONFERENCE 2018

Celebrating 10 years of the CMC: Pushing the Boundaries of Knowledge

EMERGENCY, MEDICAL & RELATED INFORMATION

Event: Salt Tectonics Field Seminar: Diapirs and Associated Deformation (Field Short Course 2).

Instructors: Dr. Ian Davison

Dates: Wednesday, August 22 to Saturday August 25, 2018 inclusive

Location(s): Coastal outcrop sections in the Mabou and Port Hood areas, Cape Breton, NS

Emergency Services

In cases of emergency, dial 911. Since we are spending most of our time in rural areas, policing is undertaken by the Royal Canadian Mounted Police – RCMP. They and local emergency organizations will be the first responders. Detachments are located in the towns of Inverness and Port Hawkesbury.

- Inverness: 1 (902) 258-2213
- Port Hawkesbury: 1 (902) 625-2220

Medical Services

There are excellent regional hospitals / community medical centres in reasonably close (<20-80 km / 15-50 miles / 20 minutes to one hour) proximity to the sites we will be visiting:

EVANSTON (PORT HAWKESBURY), NS

Strait Richmond Hospital

138 Hospital Road

Evanston, Richmond County, Nova Scotia

B0E 1J0

Tel: 1 (902) 625-3100

Operations: Open 24 hours

<http://www.nshealth.ca/locations-details/Strait%20Richmond%20Hospital>

INVERNESS, NS

Inverness Consolidated Memorial Hospital

39 James Street

Inverness, Nova Scotia

B0E 1N0

Tel: 1 (902) 258-2100

Operations: Open 24 hours

<http://www.nshealth.ca/locations-details/Inverness%20Consolidated%20Memorial%20Hospital>



CONJUGATE MARGINS CONFERENCE 2018

Celebrating 10 years of the CMC: Pushing the Boundaries of Knowledge

Communications

All field trip sites are serviced by cell phone coverage. It may be sporadic immediately below cliffs but this is addressed by moving away from them.

Contents

Aims of the Field Trip	4
Introduction	6
Broad Cove Diapir	16
Location	16
Introduction	16
Upturned Profile	16
Diapiric Structure	17
Summary.....	18
Port Hood Diapir.....	25
Introduction	25
Location	25
Overburden Lithology.....	25
Overburden Structure	25
Diapir Structure	32
Upturned Zone Profile	32
Summary.....	33
Finlay Point Diapir	34
Introduction	34
Location	34
Diapiric Structure	34
Upturned Profile	35
Summary.....	35
Finlay Point North.....	40
Coal Mine Point Diapir.....	43
Introduction	43
Location	43
Upturned Profile	43
Diapiric Structure	44
Summary.....	44
St Rose Diapir	48
Structure and Geometry of the Diapiric Contact and Drag Zone.....	48
Summary of Outcrop Evidence to Support Diapirism	51
References.....	54

Aims of the Field Trip

This course will examine salt diapirs along coastal sections developed in a Carboniferous transtensional basin which has been subsequently affected by late Carboniferous inversion. The salt diapirs penetrate Carboniferous clastic strata of varying competence (conglomerates, sandstones, siltstones, shales and coals). The diapirs are exposed in continuous cliff sections which extend continuously for over 1 km with cliffs up to 50 m in height (hard hats are required).

Some of the diapirs have been reactivated by Late Carboniferous compression and the upturned zones adjacent to the diapirs are a combination of the original deformation associated with downbuilding diapirs and later contraction. This is similar to the history of many diapirs on continental margins, which were affected by later compression. The internal structures of the diapirs are very well exposed, but no halite is exposed at surface, although it is proven to be present at depth in wells and salt mines. The exposed diapiric strata consist of interbedded gypsum, silty red shale, limestones and dolomites.

Specific objectives of the field trip are to examine the following:

1. Development of upturned and rotated flap folds in different types of overburden buried to different crustal levels.
2. Fault patterns in overburden rocks, radial and concentric faults. Reservoir compartmentalisation and damage.
3. Development of unconformities around salt structures.
4. Salt dome topography and controls of sedimentation.
5. Internal deformation of diapirs with layered clastics, gypsum/anhydrite and dolomite interbeds.

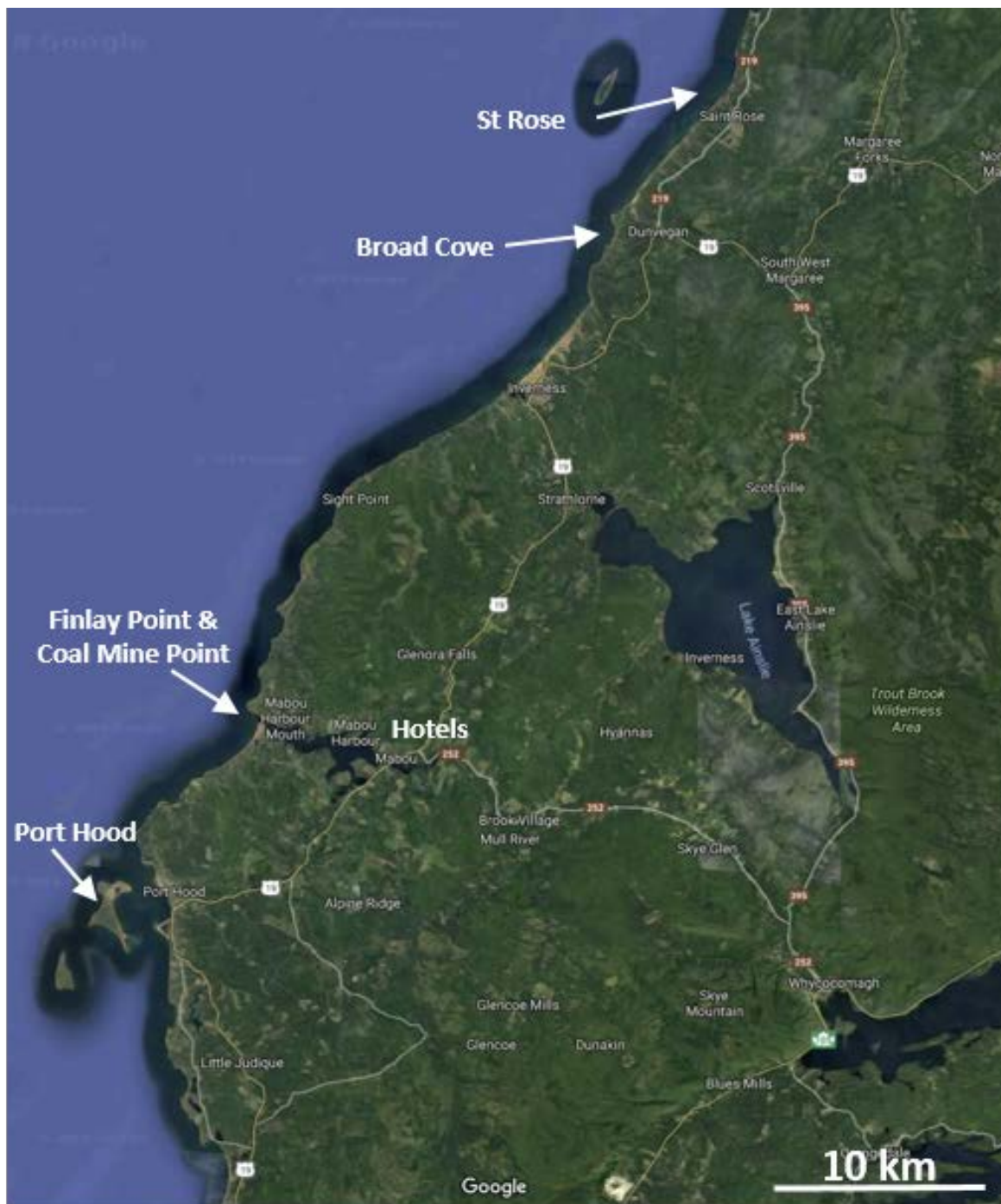


Figure 1 - General location map

Introduction

The Gulf of St. Lawrence Basin of Atlantic Canada developed immediately following the Late Devonian Acadian orogeny. The transpressional orogeny resulted in a complex collage of different terranes separated by large Paleozoic age shear zones (Gibbling et al. 2008, Fig. 2). Subsidence within the Gulf of St. Lawrence Basin continued throughout the Late Devonian, Carboniferous and Early Permian resulting in the accumulation of up to 12 km of sediment (Howie & Barss 1975). During the Late Carboniferous, the maritime region of Canada was affected by regional dextral strike-slip faulting which reactivated pre-existing structures e.g. Belle-Isle Fault, Cobequid-Chedabucto Fault and the Hollow Fault (Fig. 2). The strike-slip deformation resulted in the reactivation and/or formation of a number of small basins related to wrench tectonics which underwent rapid tectonic subsidence during the Late Carboniferous e.g. Minas Basin, Stellarton Graben, Cumberland Basin, St. Georges Basin, and the Mabou-Antigonish Sub-Basin (MASB) which forms the area of detailed field study (Fig. 1). Later inversion occurred in the late Naumurian when the diapirs were squeezed during transpression and then overlain by Westphalian Inverness Formation (Fig. 7; Gibbling et al. 2008).

Stratigraphy of the Mabou-Antigonish Sub-Basin

The Mabou-Antigonish Sub-Basin (MASB) is mainly located under the present day St. Georges Bay (Fig. 2).

The detailed stratigraphy of the area has been described by Norman (1935), Howie & Barss (1975) and Giles & Boehner (1982) and Brown (1998); Fig. 6) and the description below is based on their work.

The lowermost stratigraphy consists of the Horton Group of Devonian to Carboniferous in age which are composed continental red beds and volcanics with fluvial conglomerates and sandstones and lacustrine shales. This group can reach up to 4 km in thickness with rifting already taking place in Late Devonian times (Fig. 5a). The Horton Group is unconformably overlain by the Windsor evaporites which are distributed widely across the basin. The Windsor evaporite sequence is estimated to be 1-1.5 km in original thickness and it is estimated there is approximately 500-600 m of halite near the base of the sequence (Brown 1998). The upper section is composed of interbedded gypsum, marls, limestone and dolomite.

The overlying Mabou Group and Port Hood Formation sediments were deposited as intercalated mudstones, siltstones, sandstones and coal measures and reach up to 3 km in thickness.

The MASB is separated from the Gulf of St. Lawrence area by a basin-bounding extensional fault (Hollow Fault). The basin-bounding fault lies immediately to the north of the Huey salt wall (Fig. 4), and dips towards the south with a throw of approximately 1.5 km. The change in thickness of the Upper Carboniferous

sediments across this fault is very abrupt reducing from 2.9 km in the MASB to 0.7 km in the Gulf of St. Lawrence, over a horizontal distance of 300-500 metres.

The overlying Mabou Group and Port Hood Formation sediments are approximately 0.7 km thick. In the upper Port Hood Formation, one or more distinctive horizons (ostracod rich, high TOC black shales) dated as Westphalian A (using palynology) are present at numerous locations within western Cape Breton and at Port Hood. The deposition of these sediments and continued faulting caused differential loading which triggered the diapirs within western Cape Breton.

The Westphalian age Inverness Formation was deposited as a late to post-rift clastic blanket (Fig. 7). The Inverness Fm. within the study area is 700 m thick, consisting of intercalated coal measures, shales and sandstone units.

Sand bodies of the Inverness Formation consist of multiple stacked sandstone units (10 - 15 m thick) which combine to produce unusually thick sand bodies up to 200 m thick e.g. Gant Sandstone. Each sand unit is deeply incised into the underlying sand unit, with incisions marked by coarse channel lags containing coal fragments, reworked peat mats, abundant plant debris up to 1 m in length and mud clasts up to 15 cm in diameter. The sand bodies are interpreted as braided fluvial deposits. Some of the sandstones were probably deposited immediately after forest wildfires which destroyed all the vegetation and increased surface water run-off, thus explaining the presence of a lot of inertinite organic matter in the basal channel lags (Howard Falcon-Lang Pers. Comm. 2005).

The Inverness section has sediment transported towards both the NE and SE. The vertically adjacent sand units can have palaeocurrent that vary by up to 180°. This is not typical of braided fluvial systems and deviation of sediment transport was probably affected by salt diapir growth. Fault movements also had some control upon sediment transport direction.

Diapiric Structures, Seismic and Coastal Sections, St. Georges Bay

The salt structures extend as elongate salt walls which are exposed on the Antigonish coast (Crystal Cliffs), Port Hood Island and mainland Cape Breton (Judique Harbour) (Fig. 3). The salt walls (Huey, Luey, Duey, these names were a follow on from the Mickey salt structure in the Gulf Coast of Mexico, Brown 1998) are between 3- 4.5 km high and approximately 3 km in width (at the base, Fig. 5b). Sediment pinch-out relationships and rim syncline geometries within the Mabou Group sediments indicate that the salt structures grew passively by a continuous downbuilding process over a period of approximately 40-50 Myr. from ca. 350 Ma to 300 Ma.

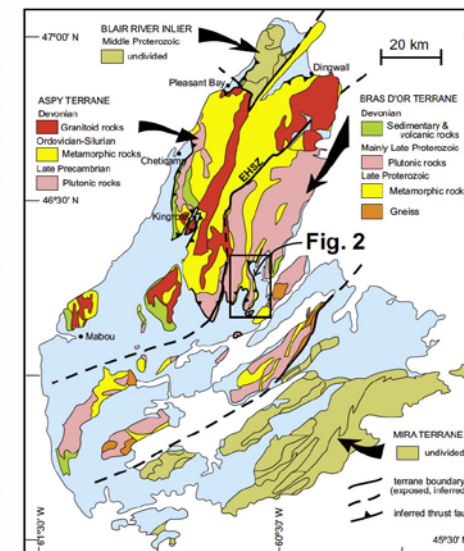
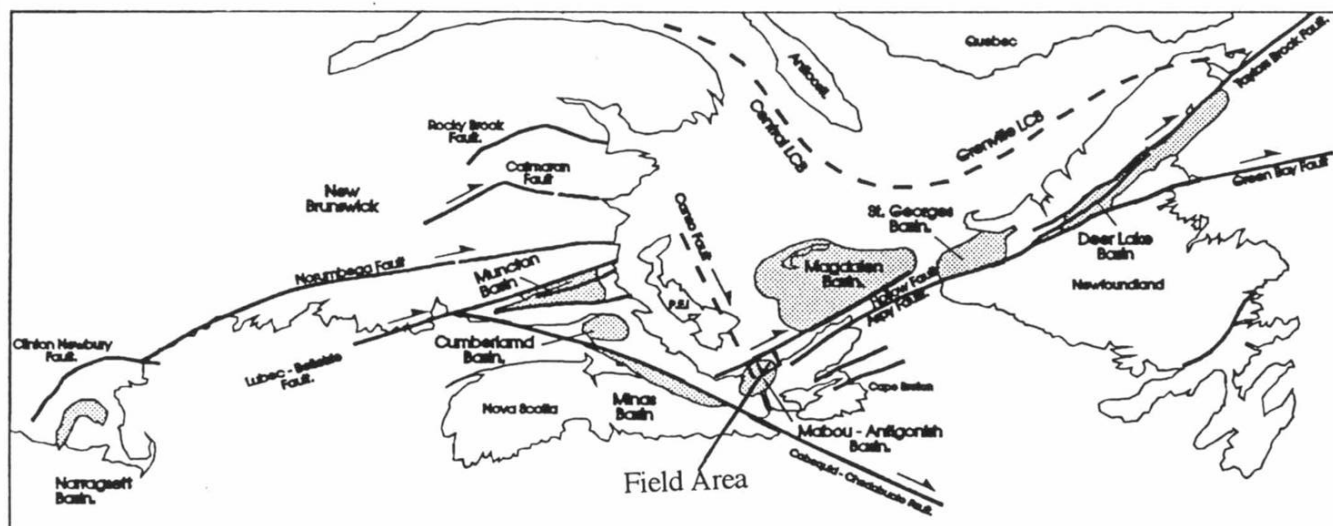


Figure 2 – a) Maritimes Basin of Atlantic Canada. Major Faults showing dextral strike-slip displacement. Displacement on the Canso Fault occurred during Mid-Devonian. b) Map of different terranes in Cape Breton (Raeside and Tizzard 2015)

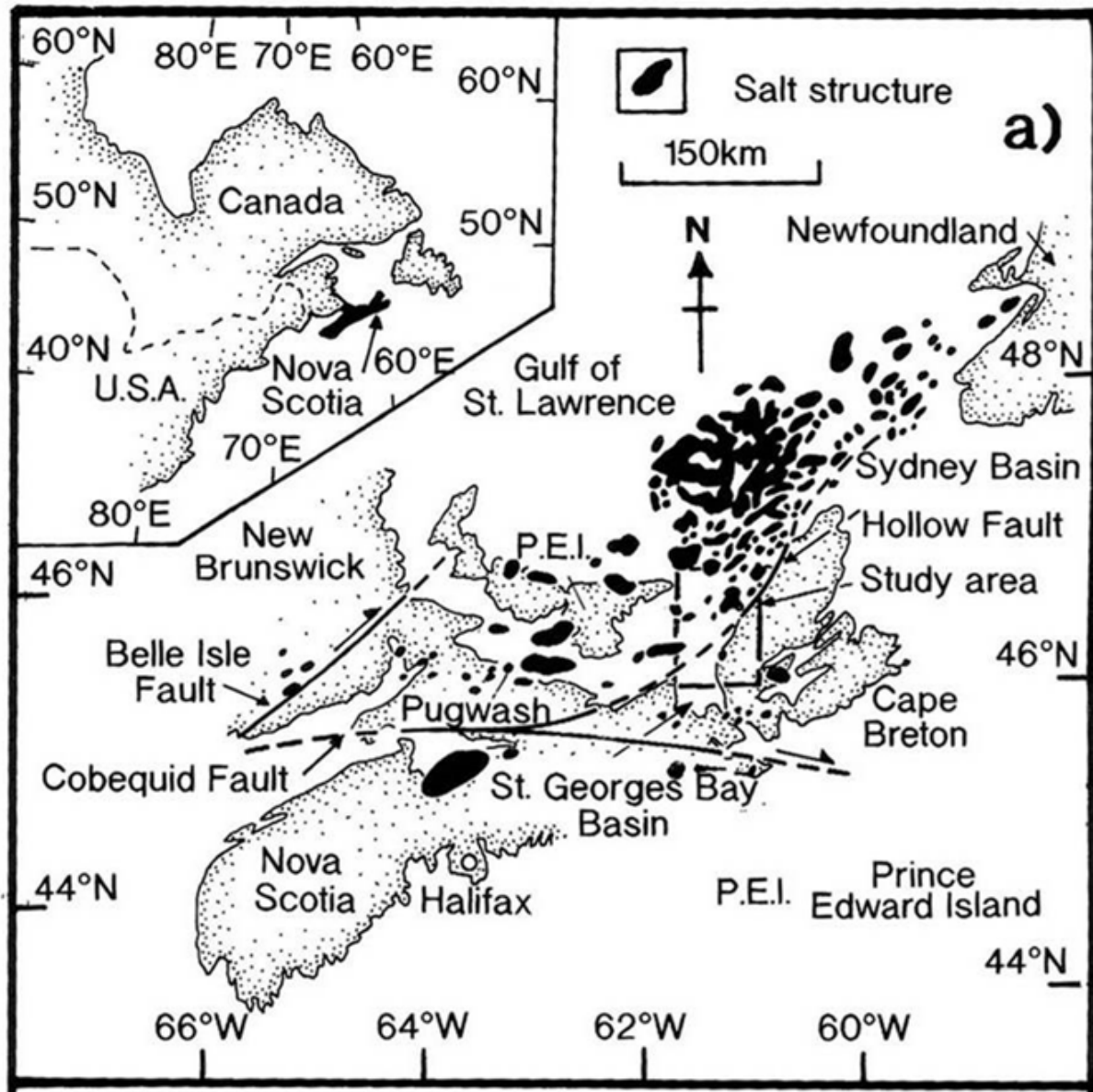


Figure 3 - Tectonic Map of Nova Scotia, showing the major faults and the location of the Carboniferous salt structures. From Alsop et al. (2000)

Geographic Location of Salt Structures

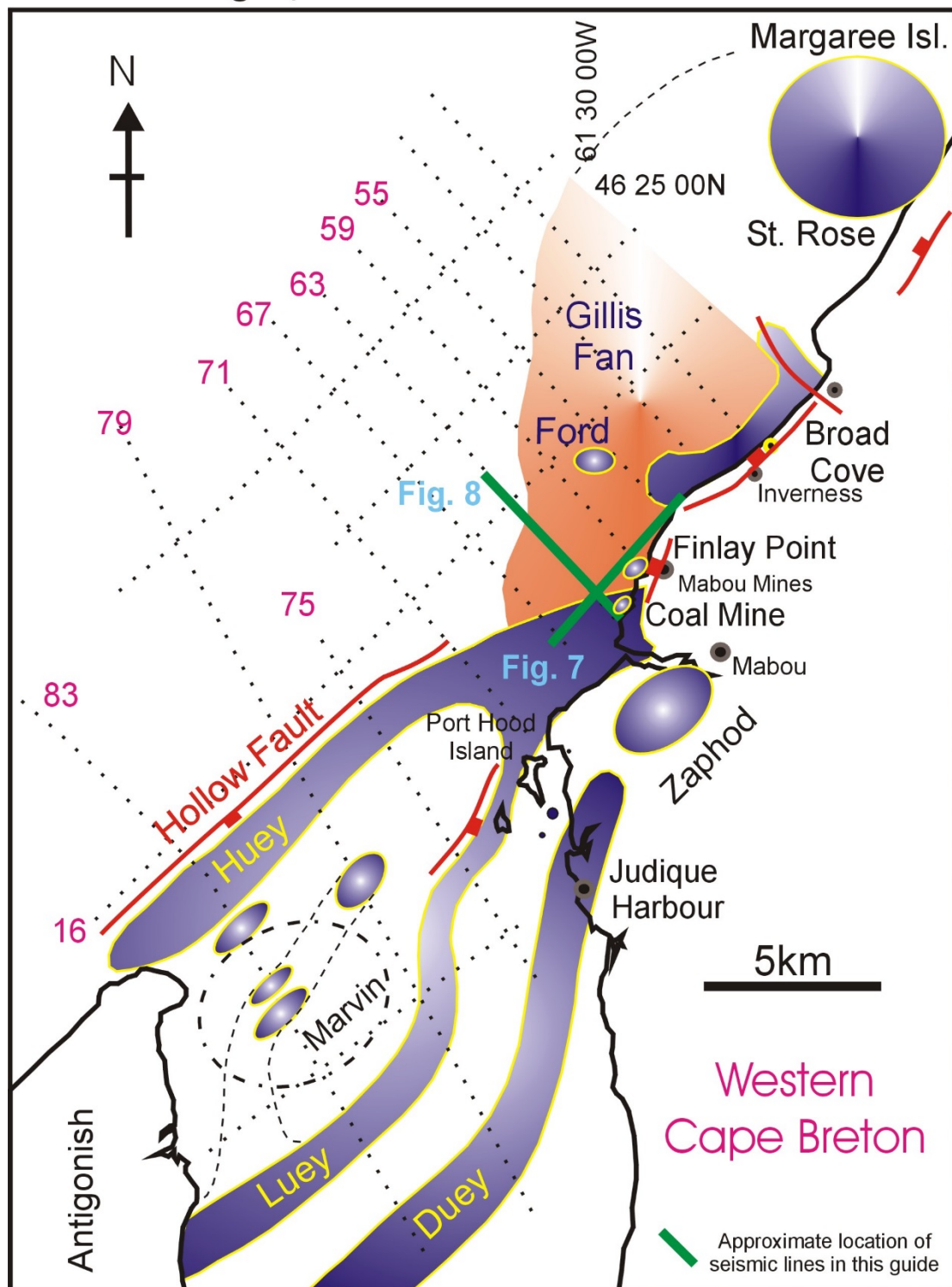
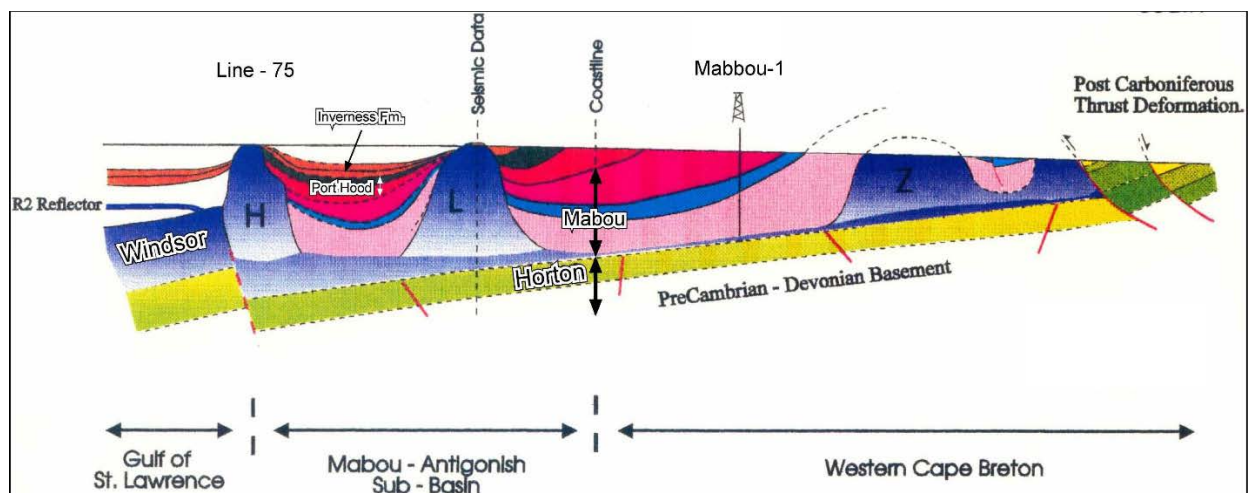
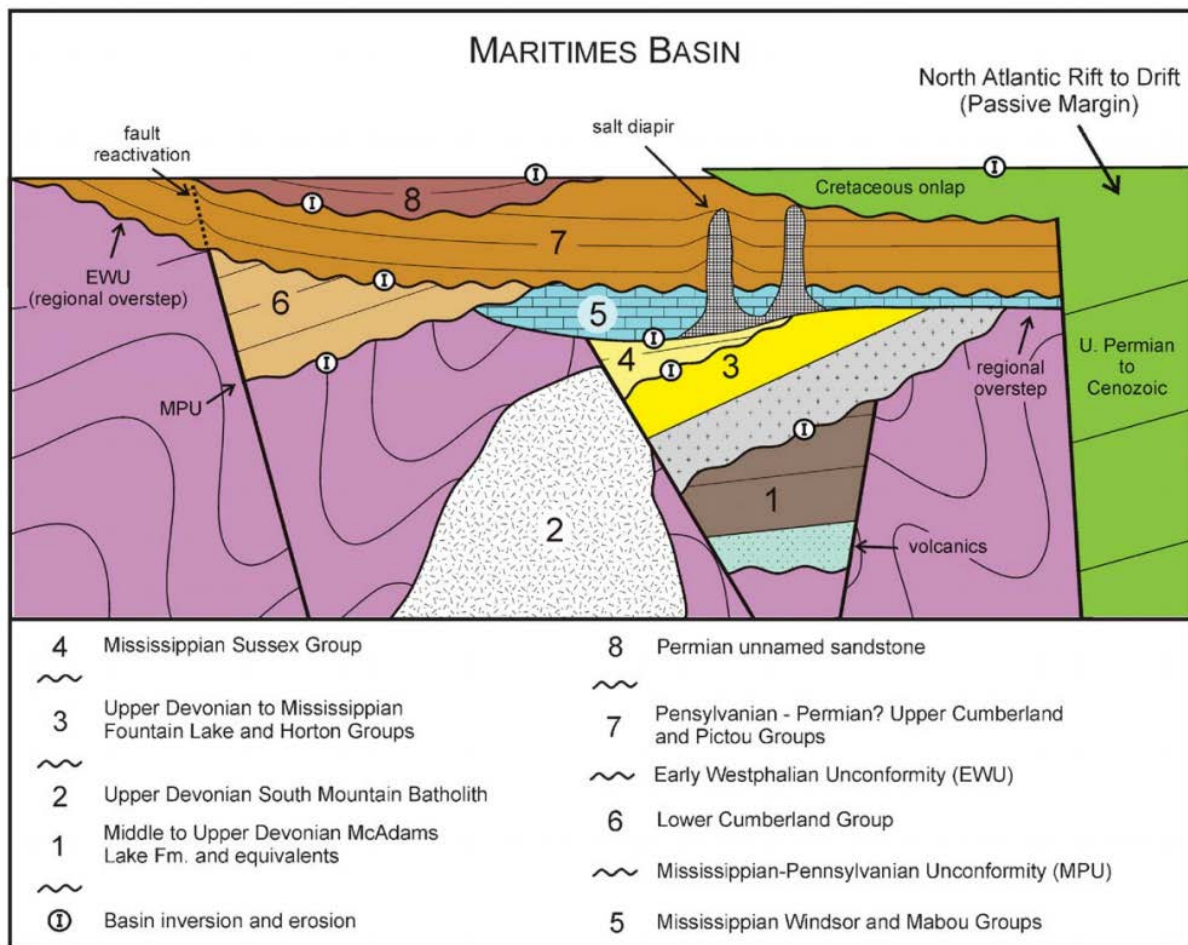


Figure 4 – Geographic location of salt structures W Cape Breton (Brown, 1998).



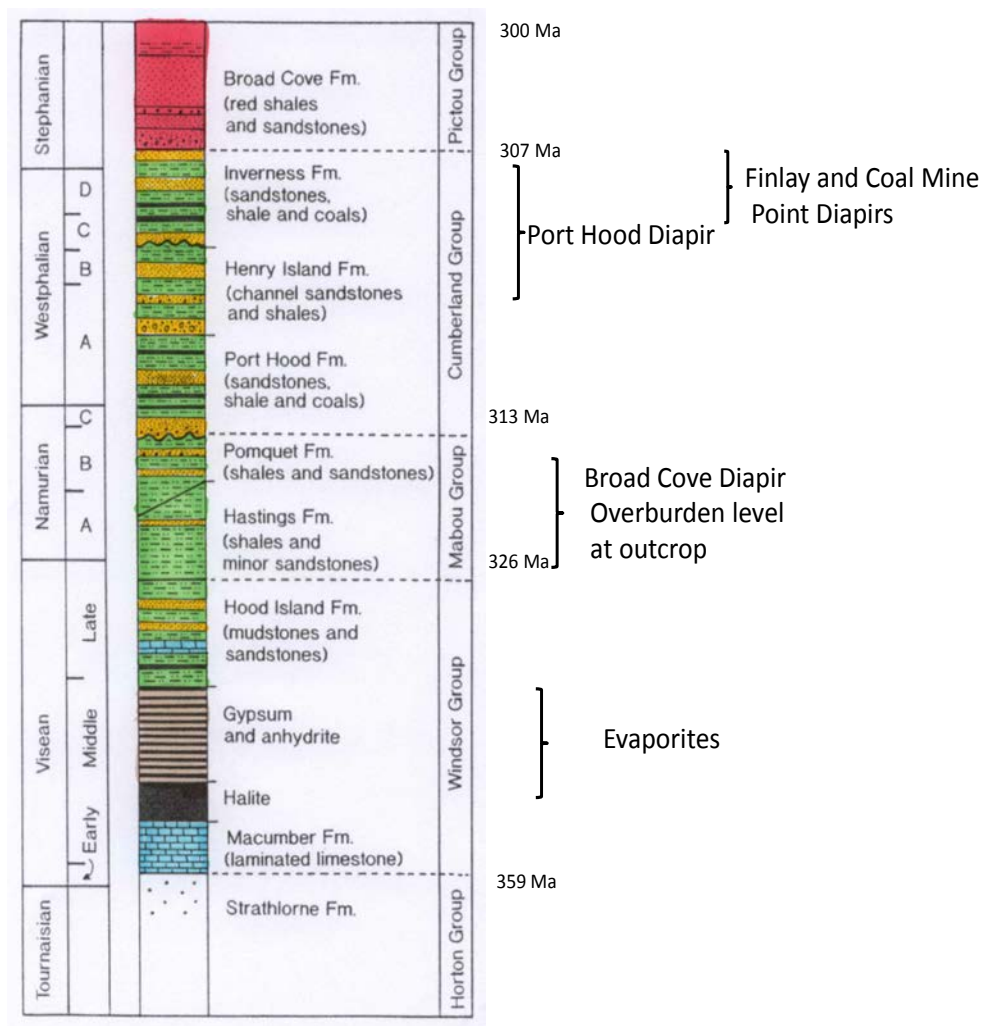


Figure 6a – Stratigraphy of the Port Hood Area, Cape Breton (modified from Alsop et al. 2000)

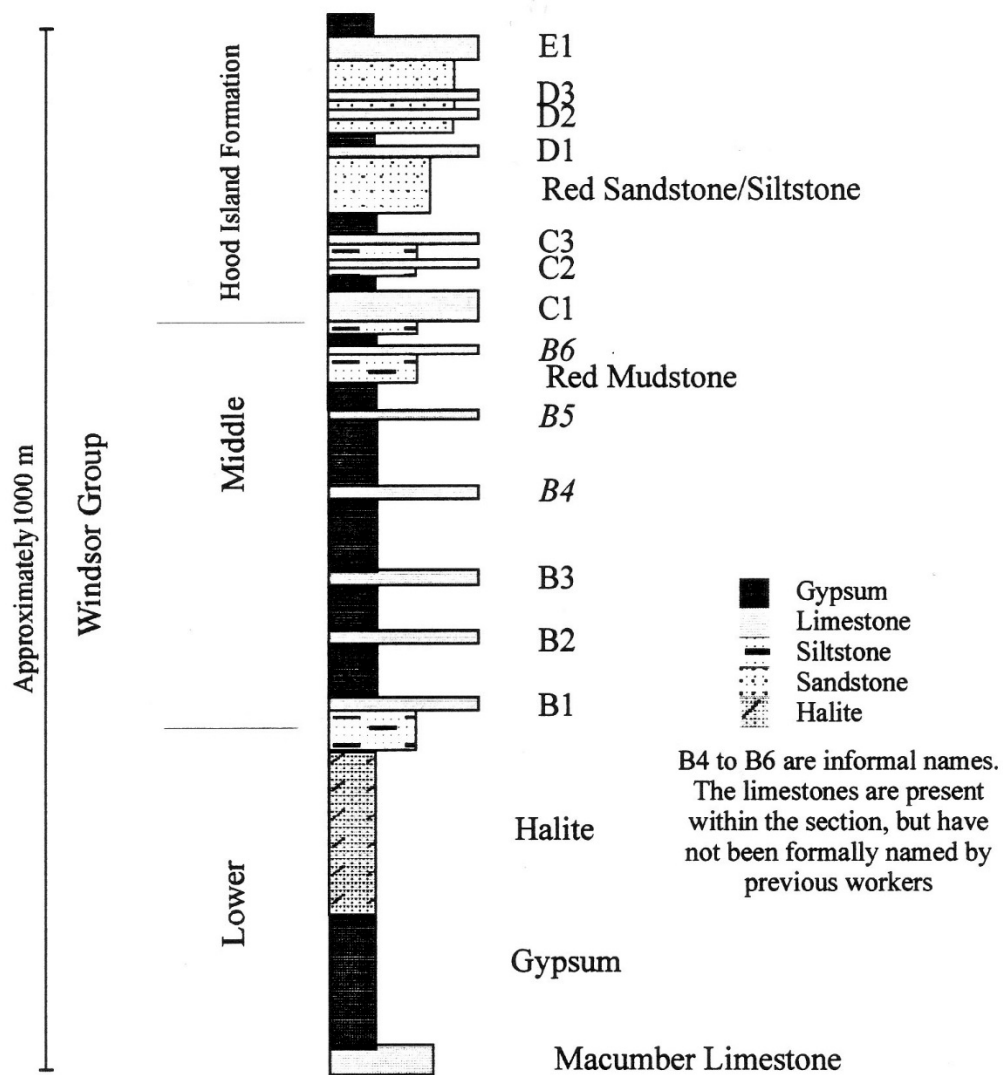


Figure 6b – Stratigraphy of the Windsor Group evaporites. After Brown (1998) and modified from Giles & Broehner (1982)

Carboniferous Stratigraphy,
Western Cape Breton,
Nova Scotia.

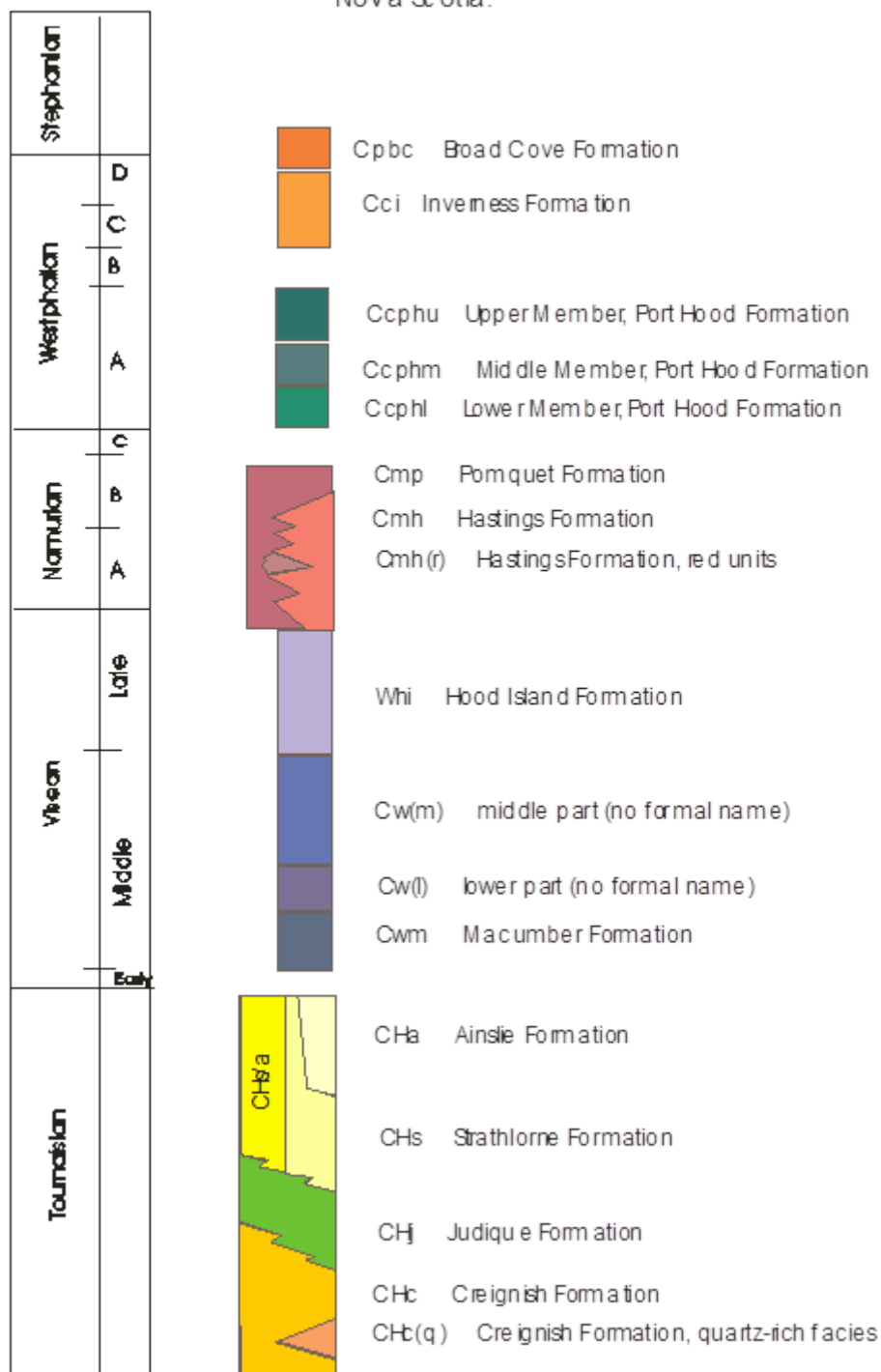


Figure 6c - Chronostratigraphy and colour coding for maps. After Brown (1998).

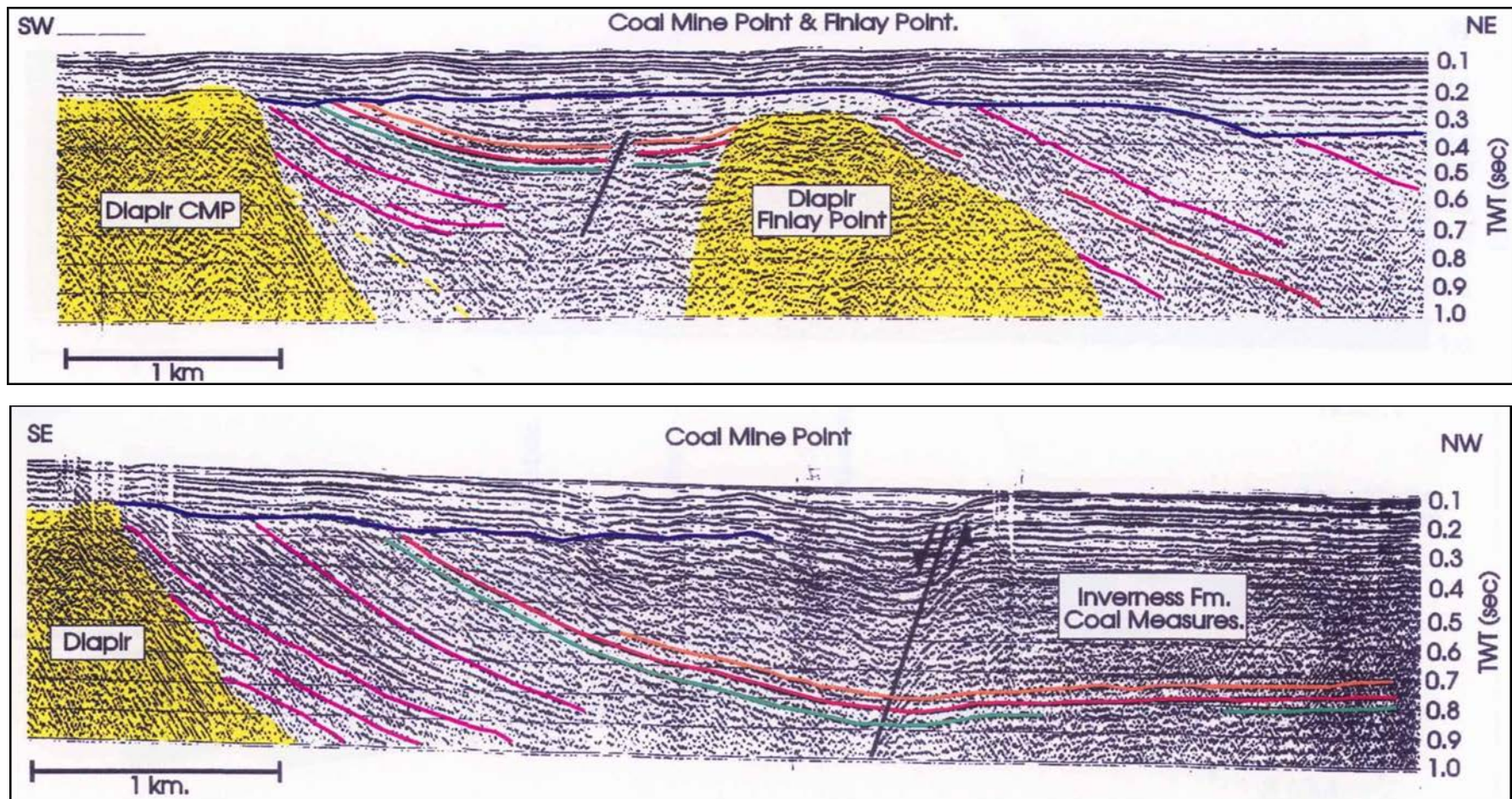


Figure 7 – Seismic section across Coal Mine and Finlay Point Diapirs (From Brown, 1998). Upwarped beds above salt are parallel bedded and folded during later compression after diapir intrusion. The age of the unconformity is Late Nuamurian.

Broad Cove Diapir

Location

Travel North from Inverness for 4 km on Route 19 then turn left towards Broad Cove Chapel. Follow the dirt road to 46° 15' 59" N, 61° 16' 07" W. Follow the stream to the beach to start the 040° trending coastal section.

Introduction

The Broad Cove Diapir is exposed in a continuous 1.1 km long section centred around Broad Cove, western Cape Breton. The NE flank of the diapir is marked by a sub-parallel contact between Upper Windsor strata and the Mabou Group sediments (Hasting Formation) which dip approximately 85° NE. The upturned zone on the NE flank extends for 600 m to the NE. Stratal dip progressively towards the diapir from approximately 22° at the northern end to slightly overturned at the southern end (Fig. 10).

Early small-scale faults (throws < 1m) have been passively rotated, maintaining a high angle to bedding (Fig. 9). Within 250 m of the diapir margin, the first generation of extensional faults strike at 090° (radial) to the diapir, whilst at distances of 250 m - 500 m away from the diapir extensional faults strike parallel to the diapir margin. The change in fault orientation can be attributed to a re-orientation of the stress field, probably related to diapir-induced stress. The later extensional faults formed as layer parallel extensional faults indicating important flexural slip took place.

The section shows a progressive rotation and steepening of right way-up bedding towards sub-vertical to overturned attitudes adjacent to the diapir whilst maintaining NW-SE strike. The broad upturned profile is punctuated by a sequence of subtle angular changes with low angle (5°) to higher angle (30°) unconformities or possible faults. It is difficult to see the contacts between different packages of stratal dips.

Upturned Profile

At the NE end of the section, the overburden is composed of red shales and siltstones together with medium-grained highly-burrowed sandstones. Bedding dips gently towards the NE, whilst minor NW-SE trending fractures typically dip steeply to sub-vertically toward the SW. Minor faults show extensional displacements of a few cm and form high angles to bedding (acute angles of 80°-90°). Localised zones of iron-stained breccia may be associated with the faults.

Reverse faults with a similar orientation to the extensional fractures and showing small (cm scale) displacements are occasionally observed.

Approximately 60 m from the start of the section, a fine-grained sandstone body forms a lensoid channel structure up to 5 m thick with erosive lower contacts. The sandstone does not exhibit enhanced fracturing.. At approximately 120 m from the start of the section, bedding in red and green shales with a 70 cm thick sandstone displays an abrupt increase in dip from 20° E to 28° E over a distance of 2-3 m. The strike remains constant at 165°, and there is no enhanced fracturing or faulting suggesting rotation of bedding has been accomplished by creep processes at the grain scale. Faults maintain NW - SE strike orientation, but show a slight reduction in dip to 70° - 80° SW. The acute angle between bedding and fractures also reduces to approximately 75°.

At approximately 180 m from the start of the section (46° 15' 52"N, 61° 16' 28"W), steeply SW dipping, 160° trending extensional fractures become more intense, although no major fault is observed. Thin (less than 20 cm) light grey-brown laminated carbonate units display soft-sediment slump and fold structures indicating transport towards the NE, away from the diapiric crest (Fig. 12). Bedding parallel faults are also observed indicating sliding away from the diapir (Fig. 10a).

At 220 m from the start of the section (~ 300 m from the diapir contact). The bedding suddenly increases in dip to 70°N. This is interpreted to be due to an abrupt angular unconformity, although the actual contact is not observed. . From this point layer parallel slip zones are frequently observed, and steep dips (70°) are generally maintained although local lower angle dips may be present due to faulting.

Diapiric Structure

The diapiric contact between steeply-dipping shales and mylonitic gypsum is marked by a zone of meter intense fracturing located at 46° 15' 42"N 61° 16' 36"W. A 1 m thick breccia zone of intensely sheared multi-coloured claystones occurs at the diapir contact indicating this is a faulted zone with intense frictional wearing. Centimetre-scale gypsum veins cut through the steeply dipping shales, as do calcite-filled open fracture systems which contain 3 mm vugs. Moderately NW-plunging mineral elongation lineations within the diapir gypsum indicate a component of transcurrent motion across the contact. Mylonitic NW-SE trending, sub-vertical shear zones within the gypsum are up to 5 m in width, contain metre scale lozenges of weakly-deformed gypsum and may be bitumen stained. The mylonitic gypsum fabric is parallel to the diapiric contact and the steeply-dipping overburden, and may be folded by secondary steeply-plunging folds. Within the diapiric crest, the interbanded gypsum, limestone and shales define an steeply dipping curtain fold synform,

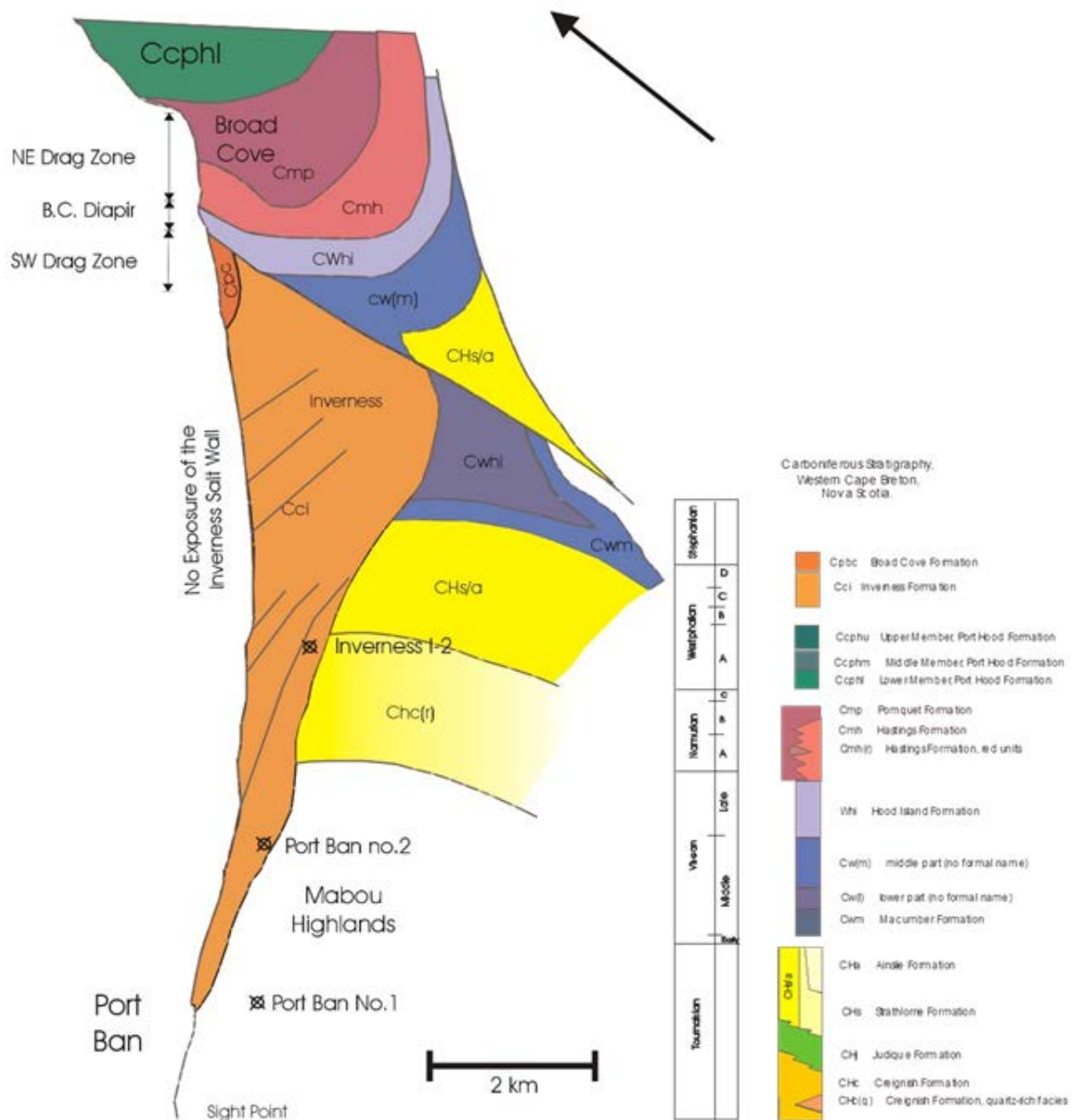
overturned slightly towards the SW which may be traced across strike for 280 m to the SW diapiric margin (see photo below).



Figure 8 - Photograph of steeply dipping curtain folds in the Broad Cove Diapir (Courtesy of Jack Richardson).

Summary

1. Throughout the overburden, minor extensional faults maintain high angles to bedding, irrespective of bedding dips, and have displacements < 10 cm.
2. A major upturned zone is developed in the overburden with a gradual rotation of bedding to the vertical over a horizontal distance of 600 m. Bedding strikes consistently NW-SE throughout the upturned zone.
3. The diapir contact is marked by vertical gypsum mylonites and highly sheared claystone breccias.
4. Isoclinal folds and sheath folds with steeply dipping axial planes indicating the level of exposure is within the diapiric neck rather than the head of the diapir.
5. Several low angular unconformities, with onlap onto the diapir, are observed and higher angle unconformities may be present were bed dip angles change abruptly although contacts are not observed.



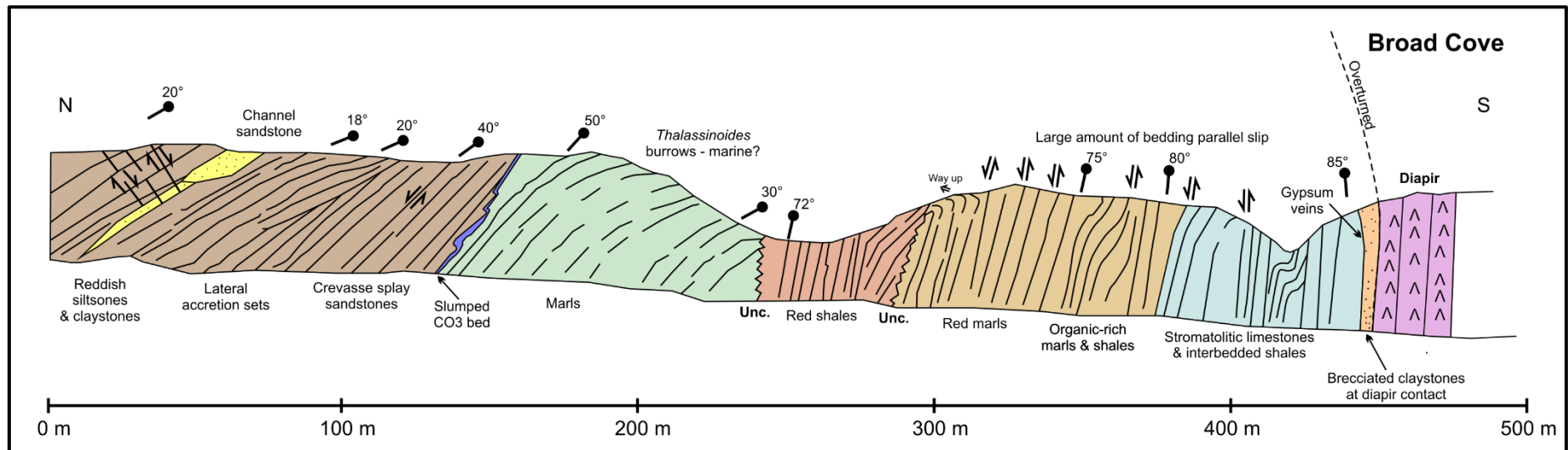
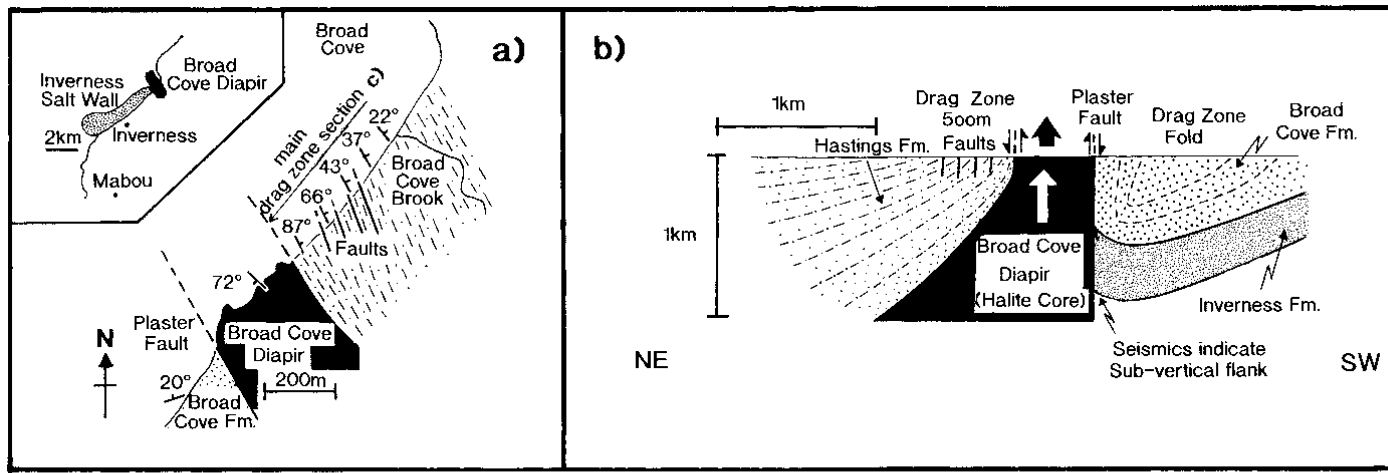


Figure 10a – map of Broad Cove Diapir upturned zones, showing rotation of Mabou Group sediment. B) regional cross section. C) Detailed cross section with two generations of extensional fault (high angles to bedding and bed parallel. Maps from Alsop et al. (2000).

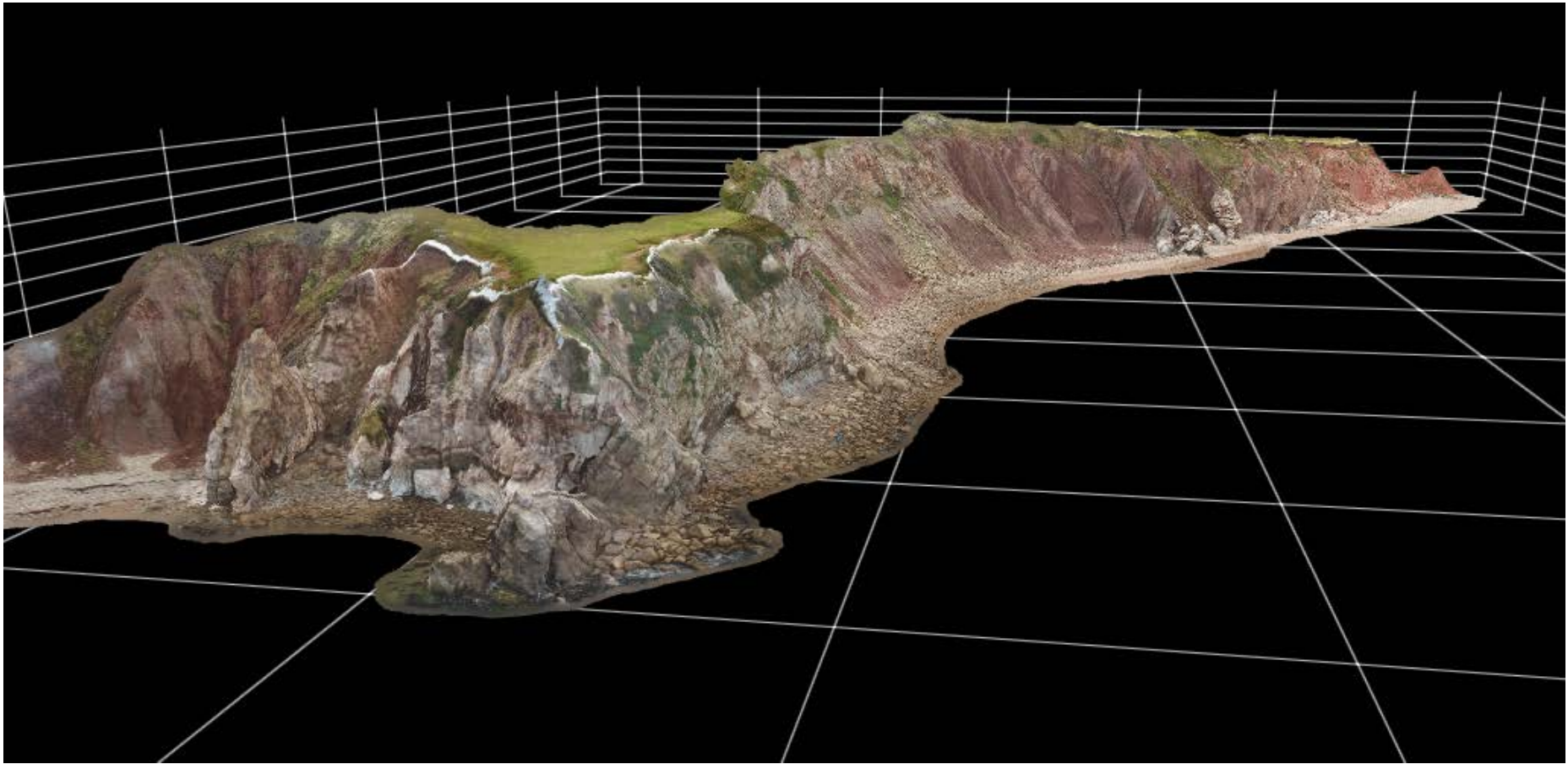


Figure 10d – Panorama looking south at Broad Cove diapir internal structure. Photographic model courtesy of Jack Richardson.

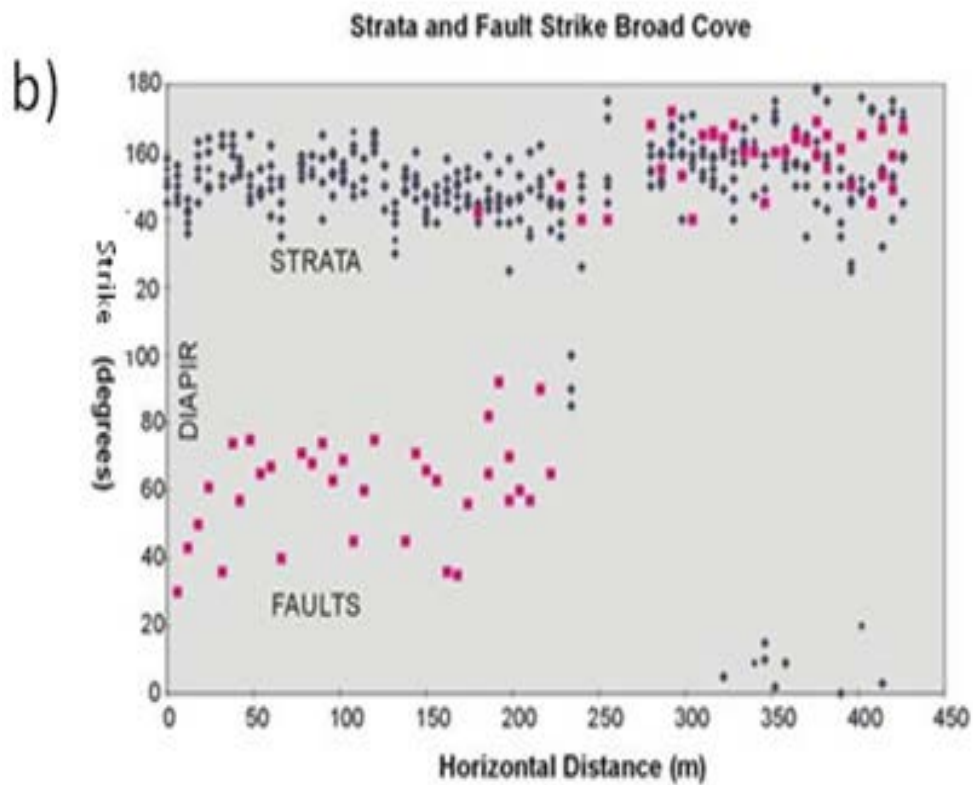
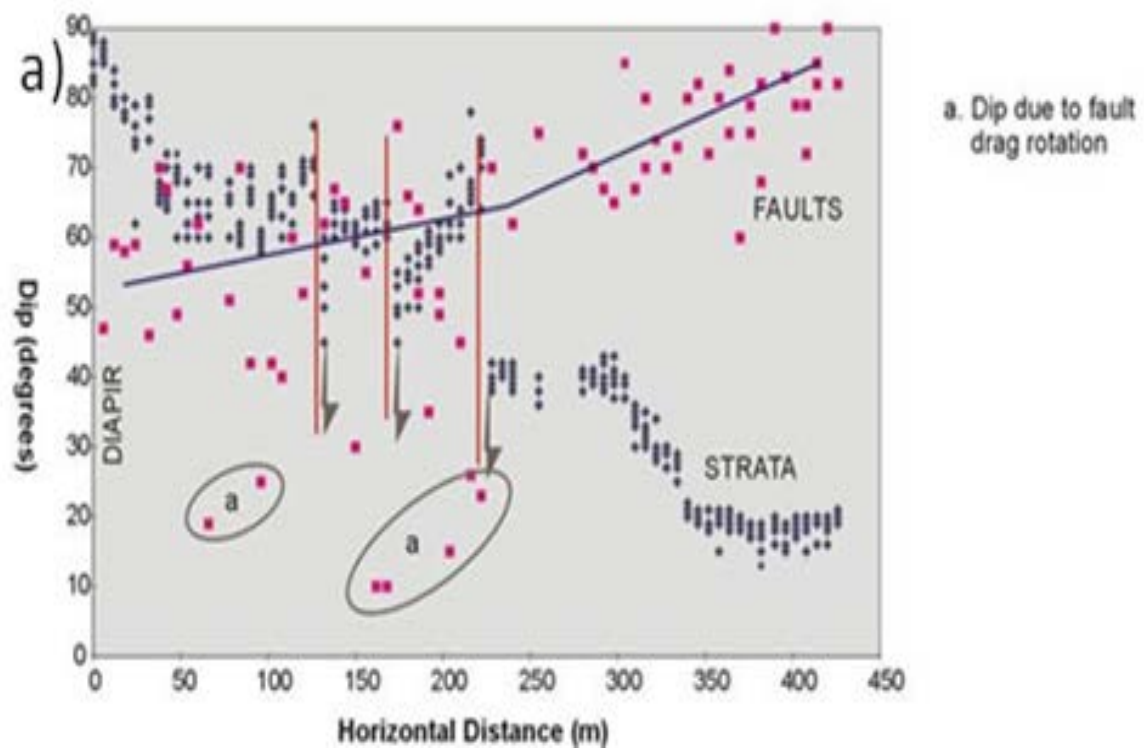


Figure 10e – Plots of a) dips of beds and b) strike of beds against distance from Broad Cove diapir wall.

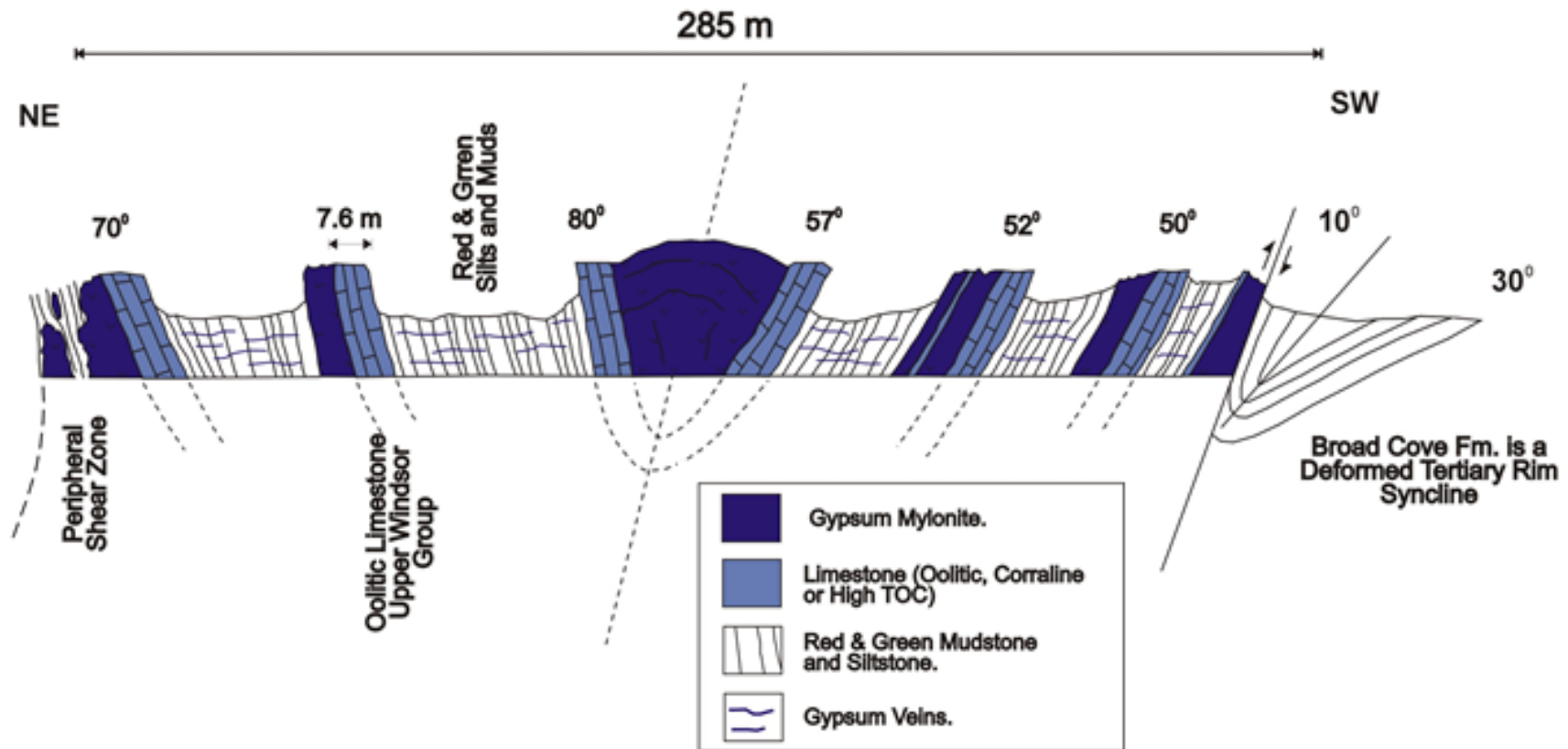


Figure 11 - Internal structure at Broad Cove Diapir (after Brown, 1998).



Figure 12a – Bedding parallel shear zones indicating extensional flexural slip away from diapir at Broad Cove.



Figure 12b – Slumping of laminated carbonate layer with vergence away from diapir

Port Hood Diapir

Introduction

Seismic interpretation indicates that the Port Hood Diapir is part of the Luey Salt Wall, which initiated in the Namurian and continued to grow as a passive diapir through the Upper Carboniferous. A narrow upturned zone is exposed at the northern tip of Port Hood Island. These strata form part of the Cumberland Group, identified only in this vicinity, where they consist of conglomerates with rounded basement and limestone clasts, sandstones, shales and siltstones. There is a relatively low competency contrast between the units despite their lithological heterogeneity, due to the unlithified nature of the sediments when diapirism took place.

Location

Take the ferry from Port Hood to Port Hood Island. Walk to the northern tip of the island (46° 01' 13"N 61° 33' 47"W). The excursion will examine the diapiric contacts at the northern and southern end of the diapir exposure and the internal fabrics within the diapir. Tides permitting we will walk for approximately 2 km through the diapir to the southern contact at 46° 00' 39"N 61° 34' 20"W.

Overburden Lithology

The overburden of the diapir is believed to be Inverness Formation (Fig. 14). This formation consists of reddish brown to purple siltstones with channel sandstones up to 3m thick with cross-bedding and flute marks at the base; along with poorly sorted conglomerates contained reworked coal fragments and limestone. Light grey fragments of limestone are reworked from the underlying Windsor Formation, indicating local uplift and erosion of this formation

Overburden Structure

The width of the highly upturned overburden is approximately 100 m. The beds dip sub-horizontally at the northern tip of the island and then abruptly increase in dip towards the diapir reaching dips of 85° at the diapiric contact. There are several smaller faults affecting the diapir, but no major faults have been recognised and the deformation mechanisms affecting the overburden are not clearly defined.



Figure 13 – Major slump fold on foreshore Port Hood Island, interpreted to have been caused by downslope sliding of unconsolidated sediment off the diapir. Yellow line indicates bedding trace



Figure 15 – Flattened gypsum nodules at margin of Port Hood diapir cross-cut by later gypsum-filled tensional gashes.



Figure 16 – Late gypsum rosettes overgrowing the early gypsum mylonite fabric indicating late fluid percolation through the Port Hood diapir.



Figure 17 – Channels filled with conglomerate derived from reworking of Windsor Group limestones in Port Hood diapir overburden, indicating diapir was exposed at sediment surface in Late Carboniferous.

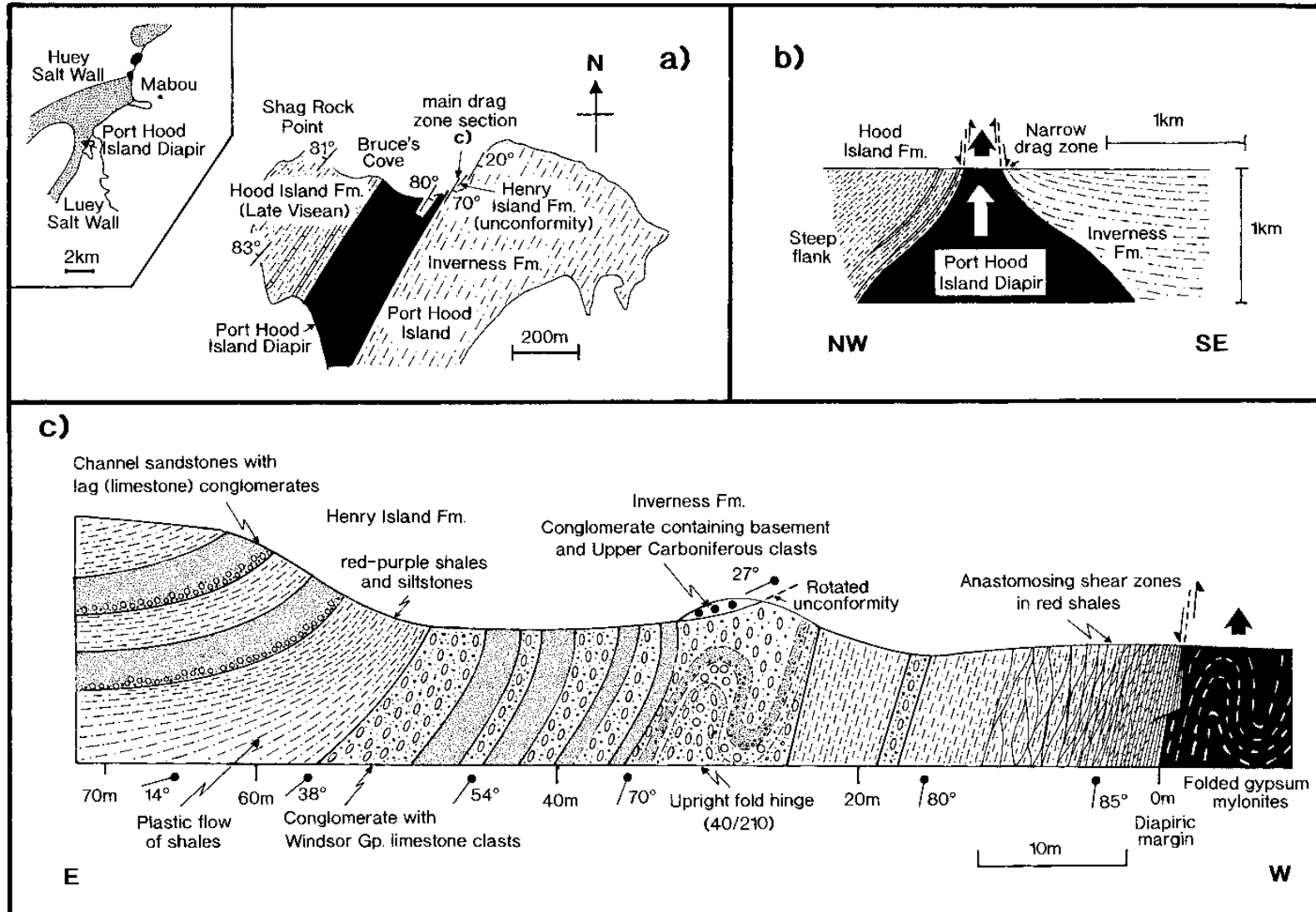


Figure 18 – Cross section and map of Port Hood diapir (After Alsop et al. 2000)



Figure 19a – Rotated J Hook unconformity at Bruces Cove, Port Hood Island (Brown, 1998).

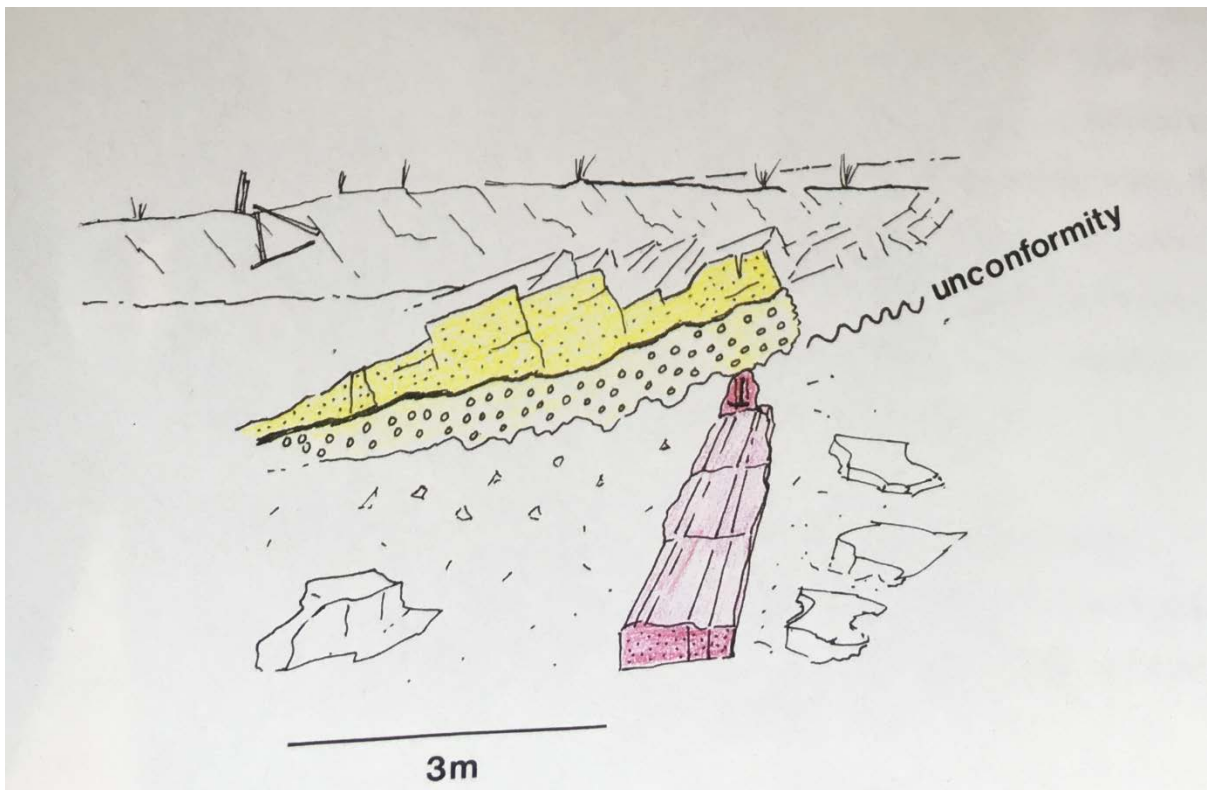


Figure 19b – Schematic cross section showing relationship between tightly folded red sandstones and polymict conglomerates below the unconformity. Overlying strata consists of channel sandstones and conglomerates.

Diapir Structure

There is a 20 m thickness of red silty shale at the contact with the diapir. This has been highly sheared with scaly shear zones spaced at a few tens of centimetres apart. These shear zones affect a zone approximately 10 m wide. The diapiric contact has been faulted by low-angle thrust faults. The gypsum inside the diapir is highly deformed and nodular gypsum indicates a fabric which is strongly prolate (stretching in one direction), but with a horizontal stretching lineation, which may be produced by folding of an initial flattening fabric (Fig. 15). The diapir contact dips outwards from the centre of the diapir at approximately 80° (Fig. 18). The diapir consists of interbeds of gypsum and red shales which are interbedded on a decametric scale, along with oolitic and stromatolitic limestones up to 5 m in thickness. The bedding is tightly folded with sub-vertical fold axes throughout the section. The red marls are often intensely veined with fibrous gypsum filling the veins. These were produced by hydraulic fracturing of the rocks where fluid pressures were close or at lithostatic pressure (Fig. 20).

Upturned Zone Profile

The width of the upturned zone is approximately 70 m, with initially sub-horizontal bedding dip increasing from the northern tip of the island to sub-vertical at the diapiric contact. Only minor faulting affects the upturned zone, which suggests that the overburden was unlithified during deformation. In the outer part of the upturned zone, the bedding rotates through 40° in less than 20m, but without faulting associated with this sharp bend, indicating that the strata deformed in a ductile manner to accommodate deformation. In these zones, the lithology consists mainly of 'weak' shales and siltstones. Closer to the diapir, sandstone beds are parallel to its wall and contain 40° SW-plunging slump folds 10 m in wavelength. The innermost 10m of the upturned profile comprises highly-sheared shales with anastomosing shear zones.

An angular intra-formational J-hook unconformity has been identified at 46° 01' 06N 61° 33' 55"W, with steeply dipping beds (85°) below overlain by moderately dipping (35°) conglomerates and sandstones of similar facies above the unconformity (Fig. 19). No slip surfaces have been recognised along the unconformity. The sequence below the unconformity is folded by large slump folds with rounded hinges and interlimb angle of approximately 40° (Fig. 13).

This was followed by deposition of the overlying conglomerates and sandstones of the Cumberland Group, which were then rotated away from the diapir by 30° during further movement of the diapir. The relationship of rotation and deformation of underlying units in the upturned zone, followed by erosion and deposition, suggests that the diapir was a topographic high. The tight folding of sediments is believed to be due to slumping off the diapiric crest during deposition of the Cumberland Group, with recumbent folds being subsequently steeply rotated. Clasts within the

conglomerates below the unconformity are formed almost entirely of micritic carbonates that were probably derived from a Windsor Group source area. Clasts in the conglomerate lenses above the unconformity include carbonate and granitic

This upturned zone profile is similar to the rotated flap folds described by Rowan et al. 2003 in the La Popa Basin, Mexico. However, we have not observed any slip surfaces along the bedding planes and the bedding rotation was probably achieved by pervasive grain boundary sliding. This diapir provides the clearest evidence for downbuilding diapirism with deformation accompanying diapir growth and was probably produced by passive flap fold rotation after the beds were deposited across the top of the diapir shoulder.

Summary

1. A narrow (approx. 100 m wide) upturned zone is developed in the overburden next to the Port Hood Diapir.
2. The reason for such a narrow zone of deformation is due to the downbuilding mechanism of the diapir during deposition of the Cumberland Group.
3. The deforming strata consist of shales and siltstones which were shallowly buried and poorly lithified before deformation; this is corroborated by the lack of faulting in the upturned zone.
4. The rotated unconformity indicates that significant movement of the diapir must have occurred with a 50° rotation of the underlying sequence before deposition of the overlying unit.



Figure 20 – Red siltstones within the diapir showing intense hydraulic fracturing and filled with fibrous gypsum indicating high paleo-fluid pressures close to Port Hood Diapir.

Finlay Point Diapir

Introduction

The Finlay Point Diapir and its associated upturned zone of overburden are exposed in a continuous 300 m section, which shows a progressive rotation of overburden from sub-horizontal bedding to steep angles adjacent to the diapir, whilst maintaining ENE-WSW strikes (Fig. 20). The upturned profile is dissected along its length by extensional faults dipping steeply NNW, and contains a 40 m wide upturned zone developed in competent conglomerates (ca. 25 m thick), which are overlain by weaker intercalated sandstones, shales and coals. These intercalations result in a moderately competent overburden, with the lithological heterogeneity causing significant competency contrasts between units.

The Finlay Point diapir is an asymmetric diapir with a steep faulted contact on its NW flank and a shallowly-dipping contact on its NE flank (Fig. 23). Interpretation of the 1978 Mabou seismic survey (Fig. 4) shows that the Port Hood Formation and Inverness Formation have been folded into a monoclinal fold adjacent to the NE contact with the Finlay Point diapir, with no stratigraphic truncation related to diapir intrusion. The folded geometry of sedimentary rocks on the NE flanks indicates that the diapir did not begin to grow until after the Port Hood Formation was deposited and lithified (Westphalian A, palynological data). The onshore exposure of the Finlay Point diapir consists of a massive, white gypsum mylonite which can be traced inland as karst topography.

By correlating the onshore section with nearshore seismic data it can be seen that the mapped upturned zone forms on the gently-dipping flank of the diapir. On the NW margin, individual conglomerate beds (<2m in thickness) are composed of metamorphosed crystalline basement from the basin margin. The overlying Cumberland Group has been upturned around the NE contact (Fig. 23).

Location

Drive south along Route 19 from Mabou, turn right (west) at sign to Mabou Harbour and follow dirt track road down to harbour. Walk to the beach at the northern side of the harbour where white gypsum cliff is exposed (46° 08' 07"N 61° 27' 46"W).

Diapiric Structure

Highly-strained gypsum adjacent to the diapiric contact trends NE-SW and dips steeply to sub-vertically towards the NW. The associated gypsum mineral elongation lineation plunges steeply towards the WSW in the plane of the mylonitic foliation. There is a progressive steepening of the gypsum foliation into sub-vertical attitudes towards the diapiric contact which is marked by a normal fault trending

170/85° W. Sandstones and shales are brecciated over a 1m interval whilst bedding dips up to 50° at the faulted contact.

Upturned Profile

The overburden adjacent to the diapir consists of red basement-derived conglomerates and coarse sandstones, these are faulted against fluvial sandstones and shales and coals.

Bedding is pervasively transected by minor extensional faults which trend NW-SE and dip gently to moderately towards the NE, where bedding is steepest. A conjugate set of NE-SW trending SE dipping faults is also developed. Minor faults are produced granulation seams which average 15 - 20 /metre within 10 m of the contact. (Fig. 24) Displacement estimates indicate 10-15 cm displacement over 1 m intervals. Fault densities in coal seams rise to 26/ metre. (Fig. 23). The microstructures in the fault planes indicate cataclasis was important suggesting there was a degree of lithification before the rocks were deformed (Rock Deformation Research Group 2006 unpublished report). Fault planes are NNE or SSE trending, and dip steeply towards the NW and are associated with down dip striae.

Summary

1. The upturned bedding zone is restricted to within 75 m of the diapiric contact, with general stratal dips not exceeding 50°, although locally they are steeper within faulted zones.
2. The upturned zone is punctuated by 2 major NNE-trending faults which have extensional displacements of >20 m (adjacent to the diapir) and 5 m.
3. Minor conjugate extensional fractures pervade the sandstones and shales resulting in overall bedding parallel extension.
4. Conglomerates adjacent to the diapir behave in a relatively rigid fashion, whilst coal seams appear to concentrate deformation with the highest fault density measurements despite being 50m away from the diapiric margins.

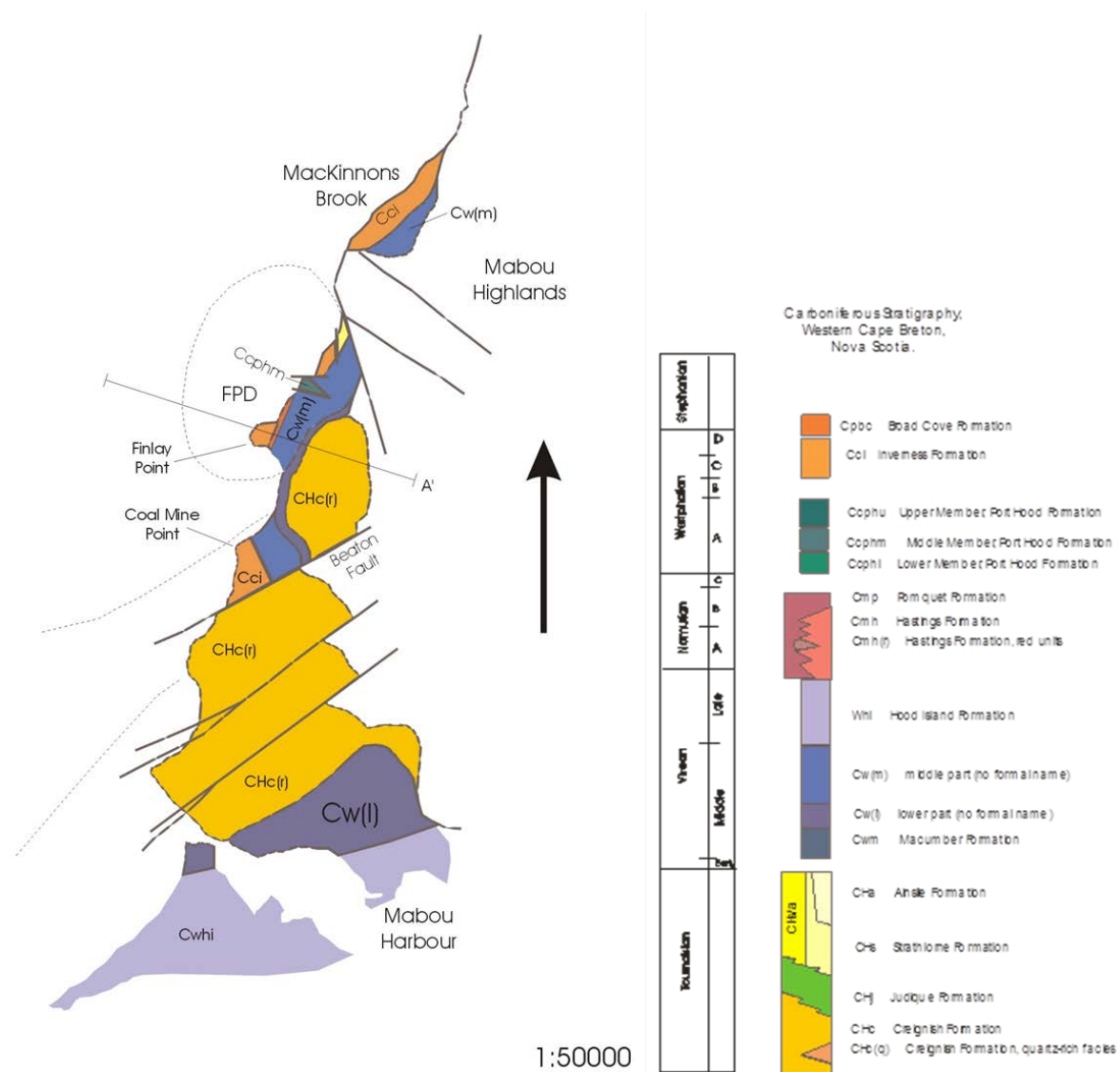


Figure 21 – Geological Map of Mabou Mines area, Western Cape Breton.

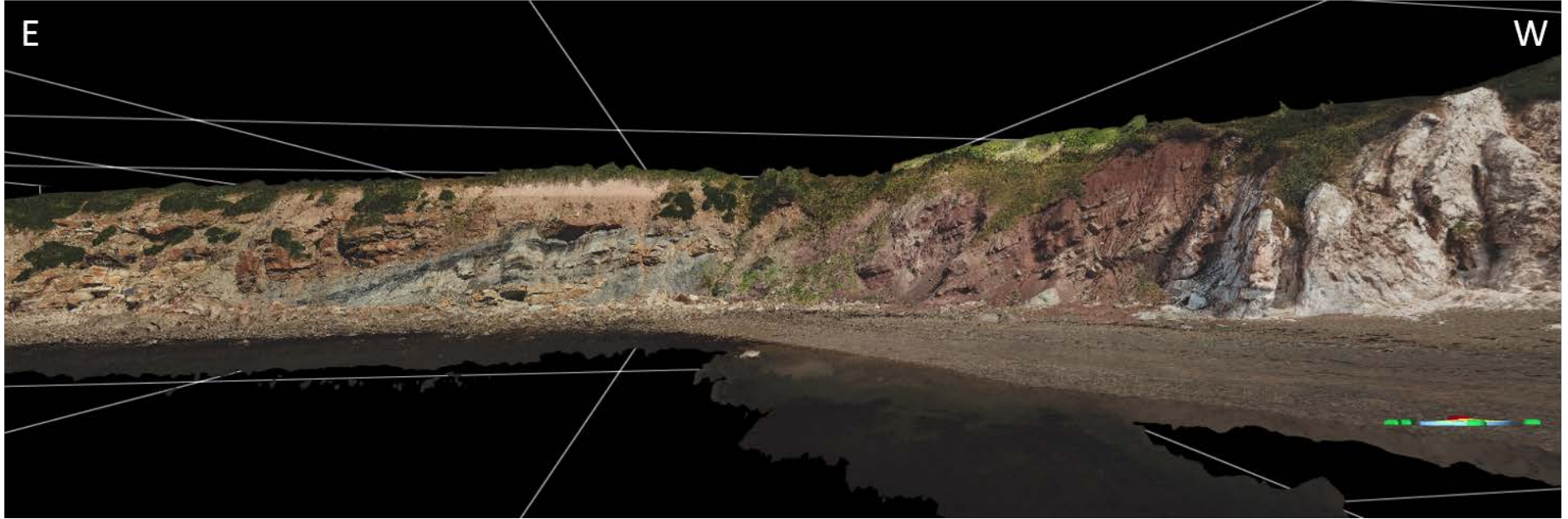


Figure 22 - Panorama photograph of Finlay Point diapir (Courtesy of Jack Richardson).

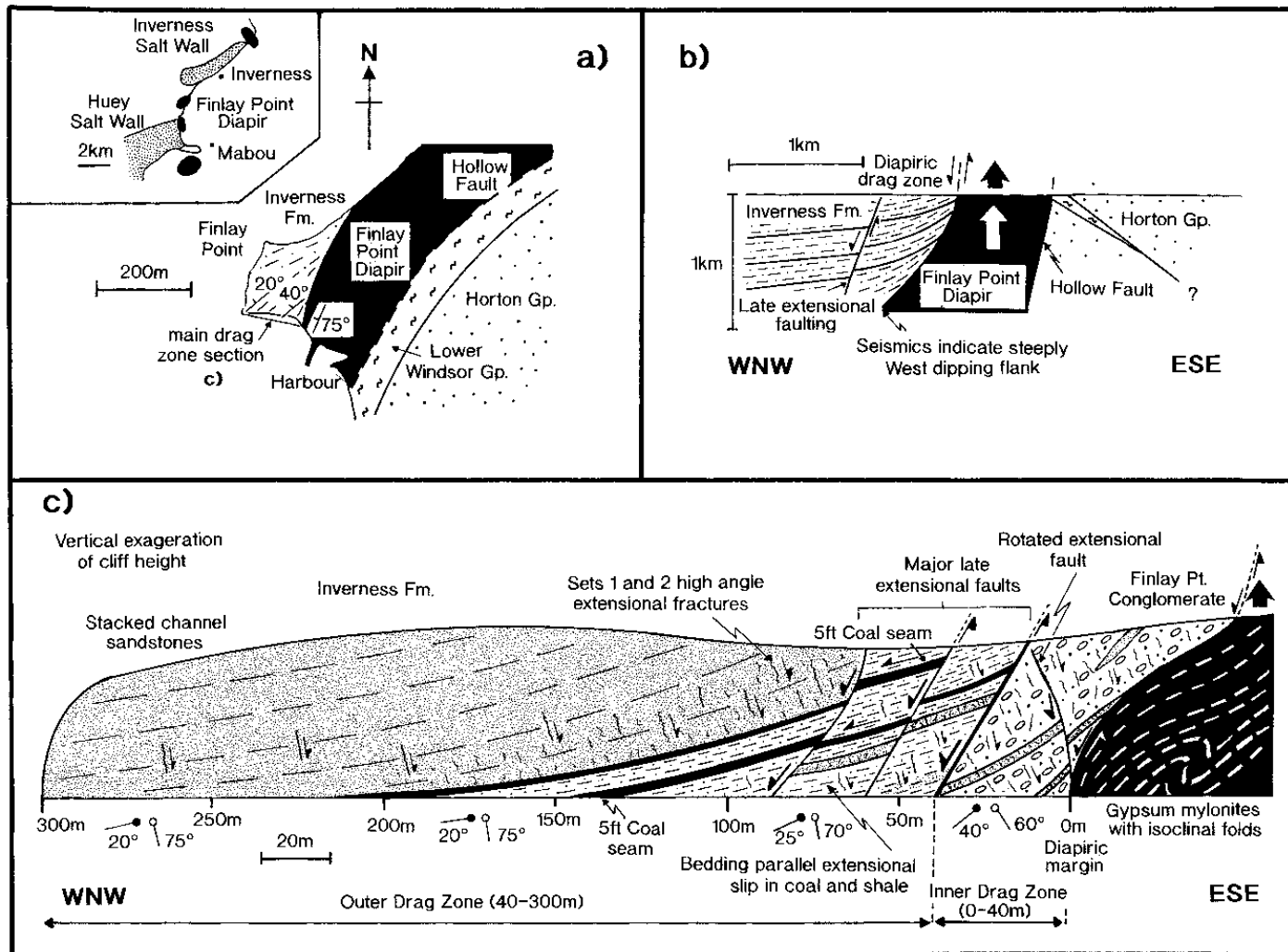


Figure 23 - Simplified geological map of Finlay Point Diapir and adjacent areas. A) The map highlights the position of the main coastal upturned zone section shown in (c), whilst the inset map shows its general location. B) Schematic WNW-ESE section illustrating the overall geometry of the diapir based on outcrop and offshore seismic data. C) WNW-ESE section through Finlay Point Diapir upturned zone, showing rotation of shales, coals and sandstones of the Inverness Formation adjacent to the diapir. After Alsop et al. 2000).

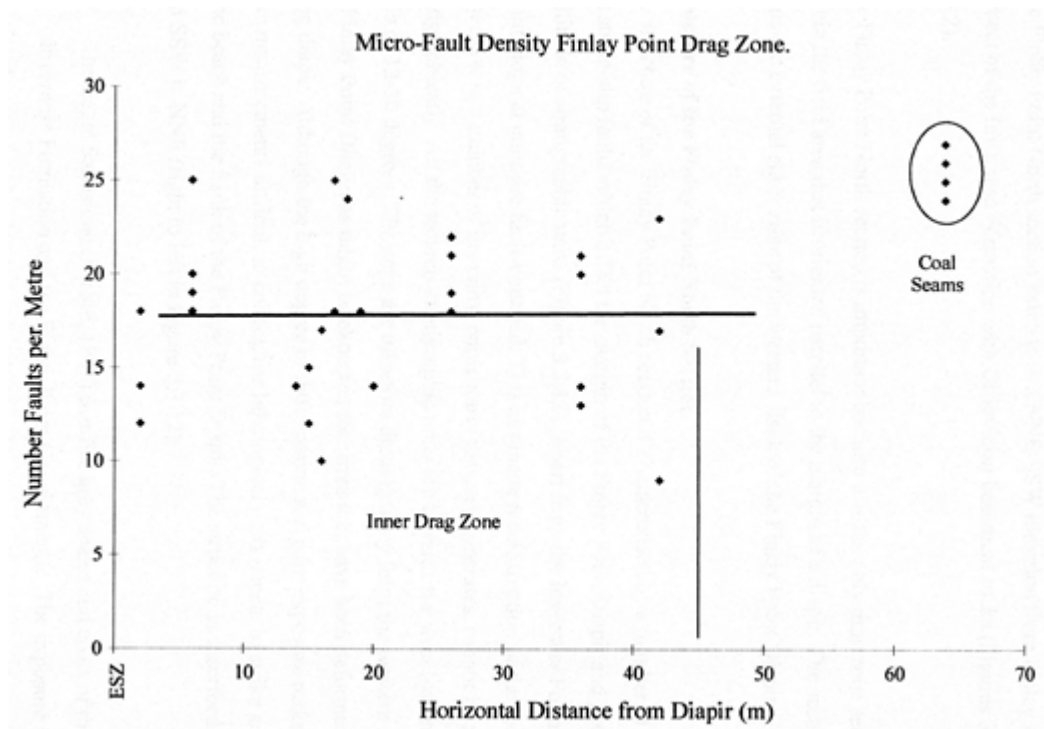


Figure 24 – Microfault density at Finlay Point diapir (after Brown, 1998).



Figure 25 – Channel lag conglomerate with charcoal fragments interpreted to be produced by wildfires with increasing surface run-off.

Finlay Point North

This section extends NNE-SSW from Finlay Point up to the contact of the Inverness Formation with Ordovician basement rocks (Fig. 18). This section is oriented parallel to the margin of the diapir. The section is very complex due to radial faults intersecting the diapir margin at high angles (Fig.25).

The Macumber member crops out at the northern end of the beach and displays spectacular folding and shearing where the most organic rich shales have acted as regional detachment surfaces.

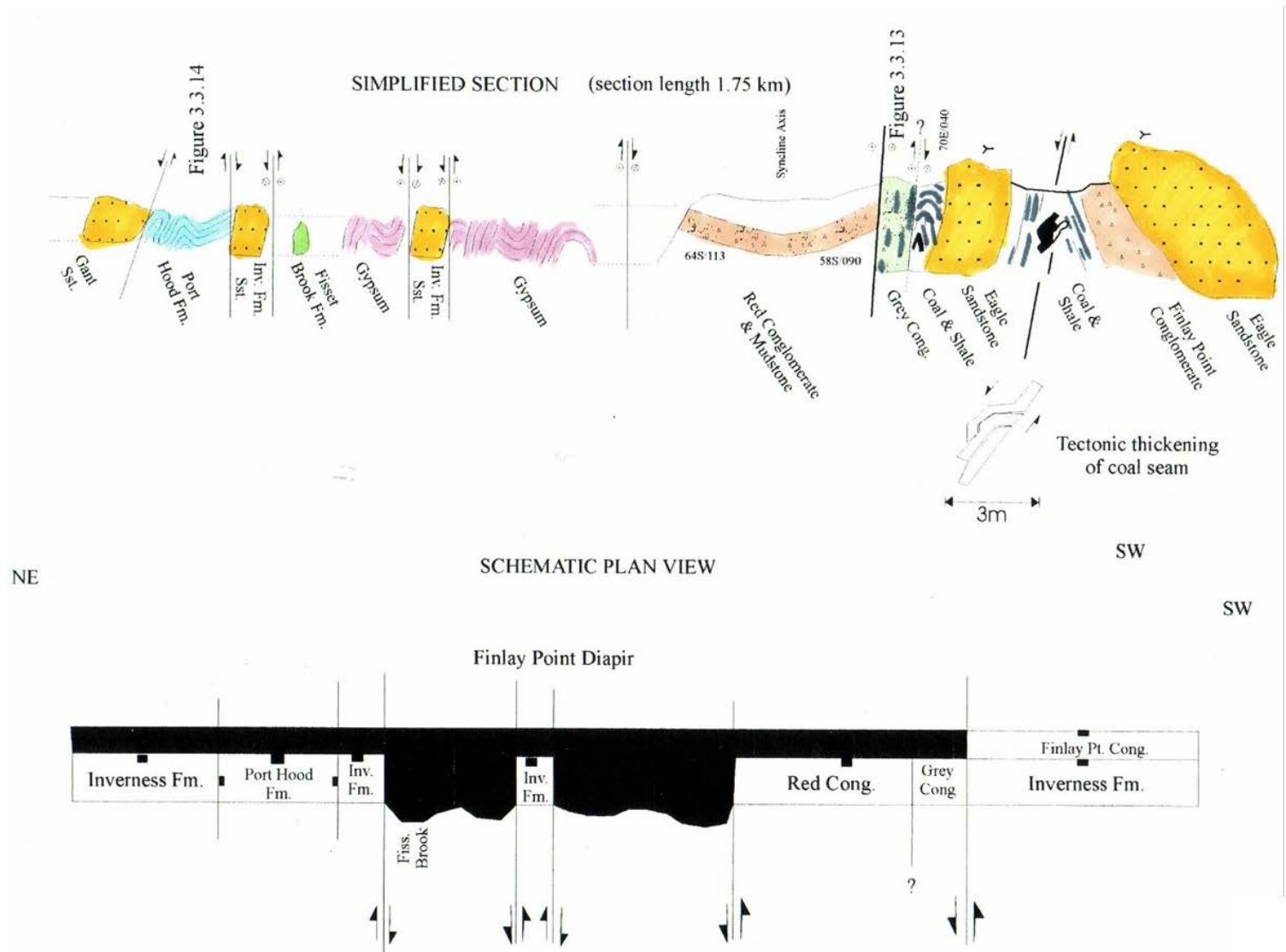


Figure 26 – Finlay Point North showing complex 'radial' faulting affecting the diapir margin (after Brown, 1998).



Figure 27 – Regional detachment zone in Macumber shales. Yellow arrows indicate discrete detachment zones in organic-rich shales.



Figure 28 – Details of detachment in organic-rich shales, showing both extensional and reverse movement. .Detachment zone is approximately 20 cm thick.

Coal Mine Point Diapir

Introduction

The Coal Mine Point Diapir is exposed on Mabou Mines beach as gypsum mylonites with the Inverness Formation draped over the northern flank of the diapir in a narrow (250 m) upturned zone (Fig. 29).

Location

Driving south along Route 19 from Mabou, turn right (west) at the sign to Mabou Harbour and follow dirt track road down towards harbour. Park at the isolated roadside house half way down the hill to Mabou Harbour, and follow the footpath behind the house down to the diapir contact.

Upturned Profile

The Inverness Formation is draped off the northern flank of the diapir in a 250 m wide upturned zone and consists of braided fluvial sandstone units up to 53 m thick (Eagle Sandstone) together with shales and coal seams. The sandstones are medium to coarse-grained poorly-sorted and sub-rounded, with some feldspar and basement clasts present. The dips of both the sandstones and coal seams progressively increase towards the diapir from 16 to 72° N. Within the thick, relatively homogenous sandstone unit adjacent to the diapir, pervasive granulation seams are developed. Granulation seams are typically less than 5 mm in width, sub-vertical, trend NNW - SSE with average displacements of 1 mm. Adjacent to the diapiric contact, granulation seams are pervasively developed with a density of 50 /metre (Fig.30). This figure gradually reduces to 25/metre at approximately 45 m from the contact. A similar measurement of 25-30 granulation seams/metre is recorded from the immediately overlying thinner sandstone approximately 100 m from the diapiric contact. . The granulation seams exhibit very little cataclasis and were probably developed when the sandstones were poorly lithified (Leeds RDR Ltd. Confidential Report 2006). The deformation within the Eagle Sandstone overlying the coal measures is restricted to a few discrete extensional faults with no joints and a few granulation seams.

The overlying Eagle Sandstone lies unconformably above the highly deformed shales and sandstones. No granulation seams are recorded with only occasional discrete minor extensional faults developed. Intervening packages of shales (up to 5m thick) and coal seams show abundant evidence of bedding parallel flexural slip and shear, with the development of striae, bedding-parallel fractures and polished surfaces. The shales and coal seams are therefore considered to have absorbed a large proportion of the overall deformation. Both the sandstones and shales are transected by NNW-SSE trending moderately to steeply E dipping oblique slip faults with striae that plunge moderately towards the SSE. Both sinistral and dextral displacements are observed on separate faults.

Diapiric Structure

The margin of the diapir is marked by mylonitic gypsum at 46° 07' 29"N 61° 27' 55"W. Developed within the plane of the mylonitic gypsum foliation is a mineral elongation lineation, which is typically gently-plunging parallel to the diapiric margin suggesting possible late stage transcurrent motion, or horizontal folding of the pre-existing fabric. Tight folding of the gypsum layering is also observed. In the shales immediately adjacent to the contact, scaley clay fabrics are developed sub-parallel to bedding whilst adjacent sandstones and thin limestones contain sub-vertical calcite veins. Internal fracturing within the gypsum results in gently-dipping gypsum veins with vertical gypsum fibre infill indicating high pore pressures greater than lithostatic.

Summary

1. Sandstones and shales/coal seams behave in different ways to deformation with high angle faulting in competent sandstones and bedding parallel slip in weaker shales and coals.
2. Granulation seams are intensely developed in the sandstone adjacent to the diapir, but display a rapid reduction in intensity away from the diapir. The sandstone farthest from the diapir shows no granulation seams suggesting deformation localisation into intervening shales.
3. Beds thin towards the diapir, and angular unconformities are observed below the Eagle Sandstone.

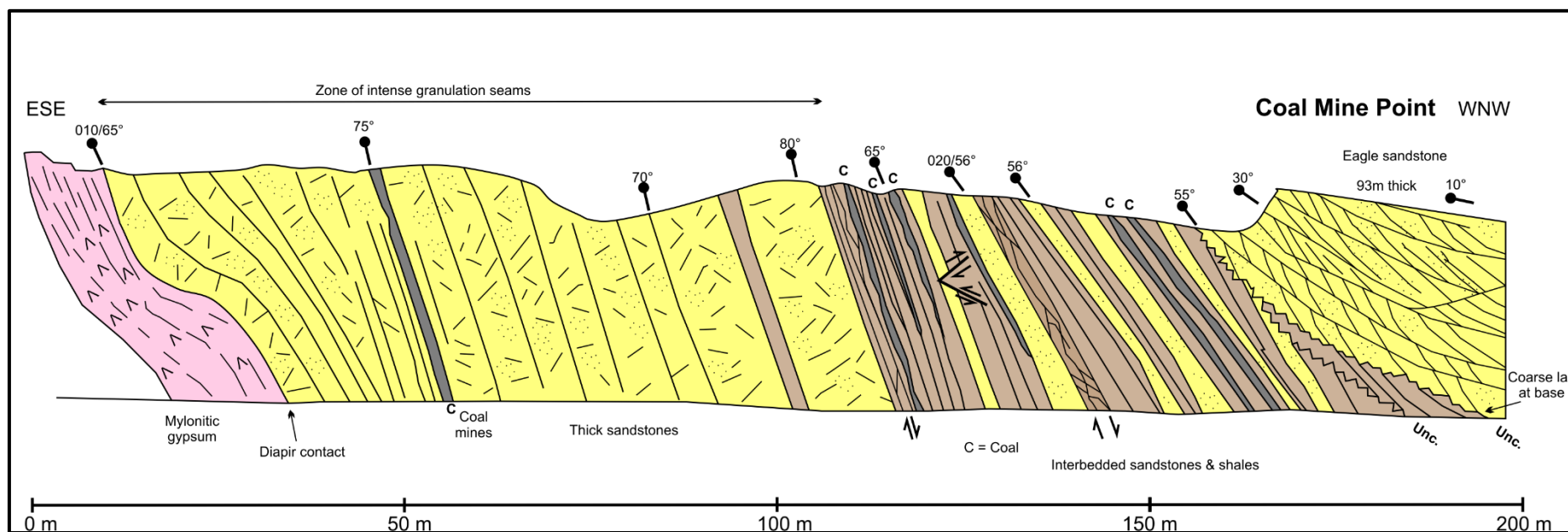
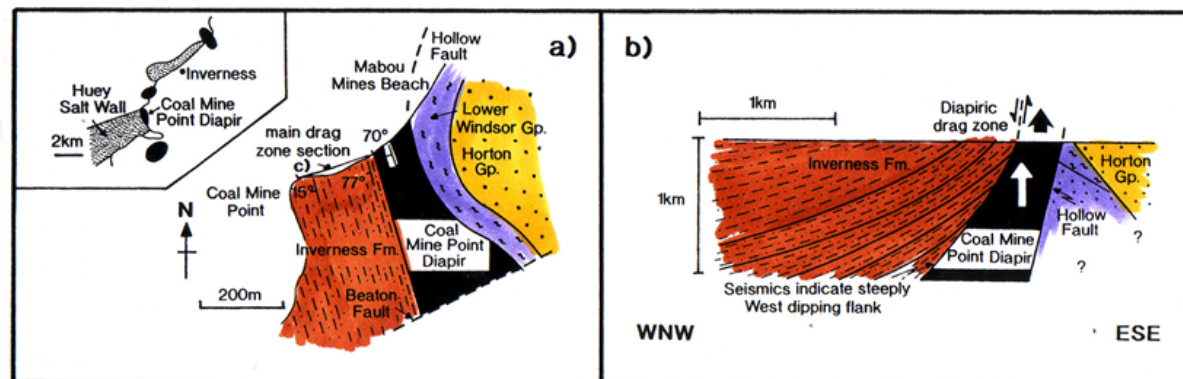


Figure 29 – Detail of Coal Mine Point diapir

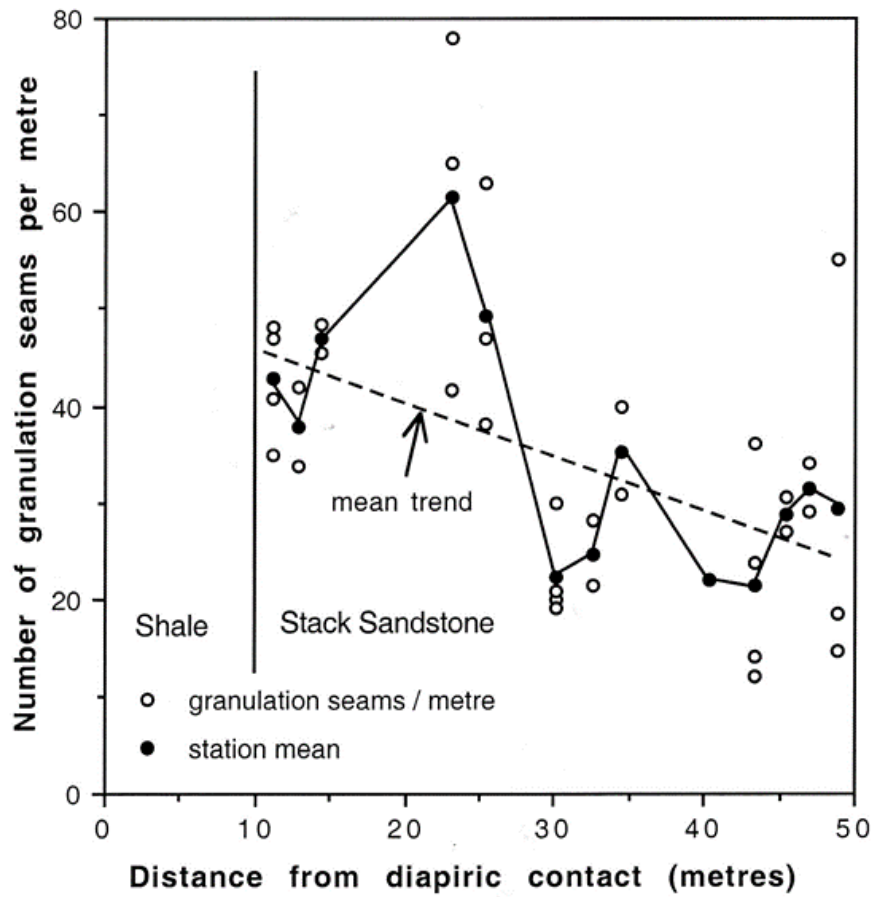


Figure 30 – A) Microfault density versus distance from the contact of Coal Mine Point Diapir (Ian Alsop, unpublished), B) detail of granulation seams at Coal Mine Point.

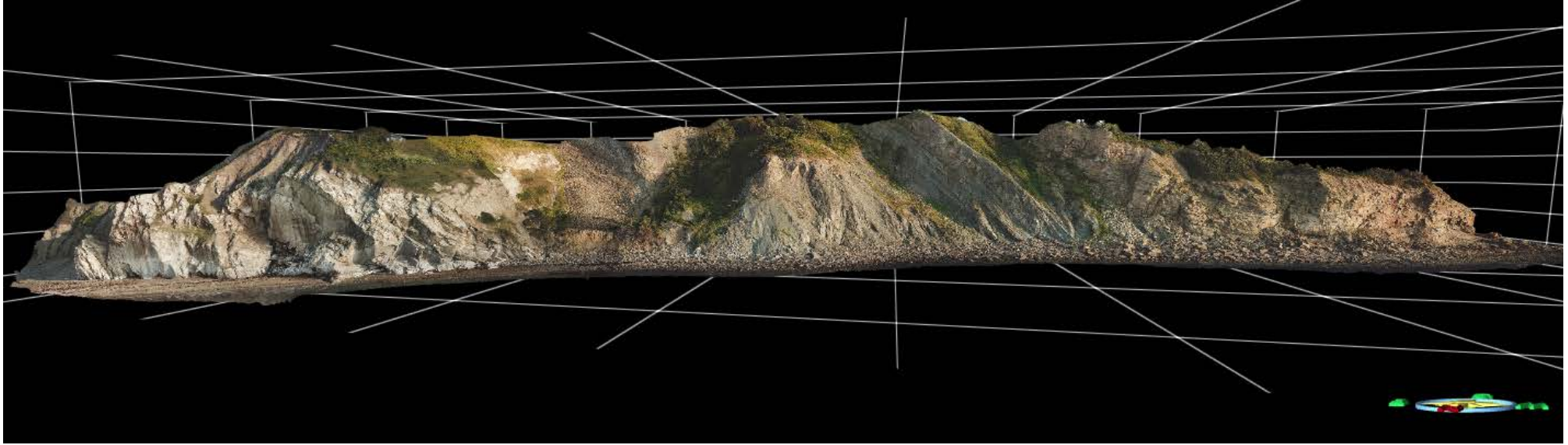


Figure 31 – Panorama of Coal Mine Point Locality (Courtesy of Jack Richardson).

St Rose Diapir

The St Rose Diapir, was first described as a diapiric structure by Haites (1952), which was inferred from onshore mapping together with coal exploration drill cores. The St Rose Diapir is around 900 m in height and has a diameter of 3–3.5 km, with the associated upturned zone containing similar structural features to that of the Broad Cove Diapir. The 450 m wide upturned zone is developed in well-bedded (at <30 cm scale) sandstones which form stacked channel units <50 m thick, together with red and grey shales (Port Hood Fm). These lithologies are considered to represent competent overburden with the lithological heterogeneity resulting in moderate competency contrasts between units.

Structure and Geometry of the Diapiric Contact and Drag Zone

The diapiric contact between steep east-dipping shales and mylonitic gypsum is marked by a 3 m thick brecciation zone (46° 21'06"N 61°11'37"W). The brecciation zone comprises limestone fragments together with randomly oriented, angular fragments of red shale, siltstone and grey sandstone set in an argillaceous matrix heavily veined by white gypsum orientated parallel to the contact. Siltstone units within the gypsum dip steeply and trend NNW–SSE. These rocks been strongly brecciated resulting in layers of stratiform breccias. Ductile deformation within the diapir generates isoclinal, intrafolial folds which are refolded by major upright closed folds plunging moderately towards the NW (Fig. 32c). Both ductile and brittle deformation increase towards the peripheral shear zone at the margin of the diapir with brecciation of gypsum, anhydrite and shales being most intense within 30 m of the contact.

The well exposed upturned zone is developed in the sandstones and shales of the Port Hood Fm. over a horizontal distance of 450 m, with bedding progressively rotated from dips of 20°E to sub-vertical attitudes, whilst maintaining NNE–SSW strikes. Throughout the overburden, minor NW–SE-trending extensional fractures maintain high angles (typically >60°) to bedding, and are steeply dipping where bedding is gentle, and shallowly dipping where bedding is steep indicating that they formed relatively early and were subsequently rotated during diapir development. Conjugate sets of granulation seams are also developed with the NW–SE-trending set perpendicular to the diapir wall. Minor conjugate extensional fractures pervade the sandstones and shales resulting in bedding-parallel extension. The broad upturned profile is punctuated by a sequence of east-dipping extensional faults which generate secondary decametric-scale drag zones superimposed on the upturned profile (Fig. 32c).

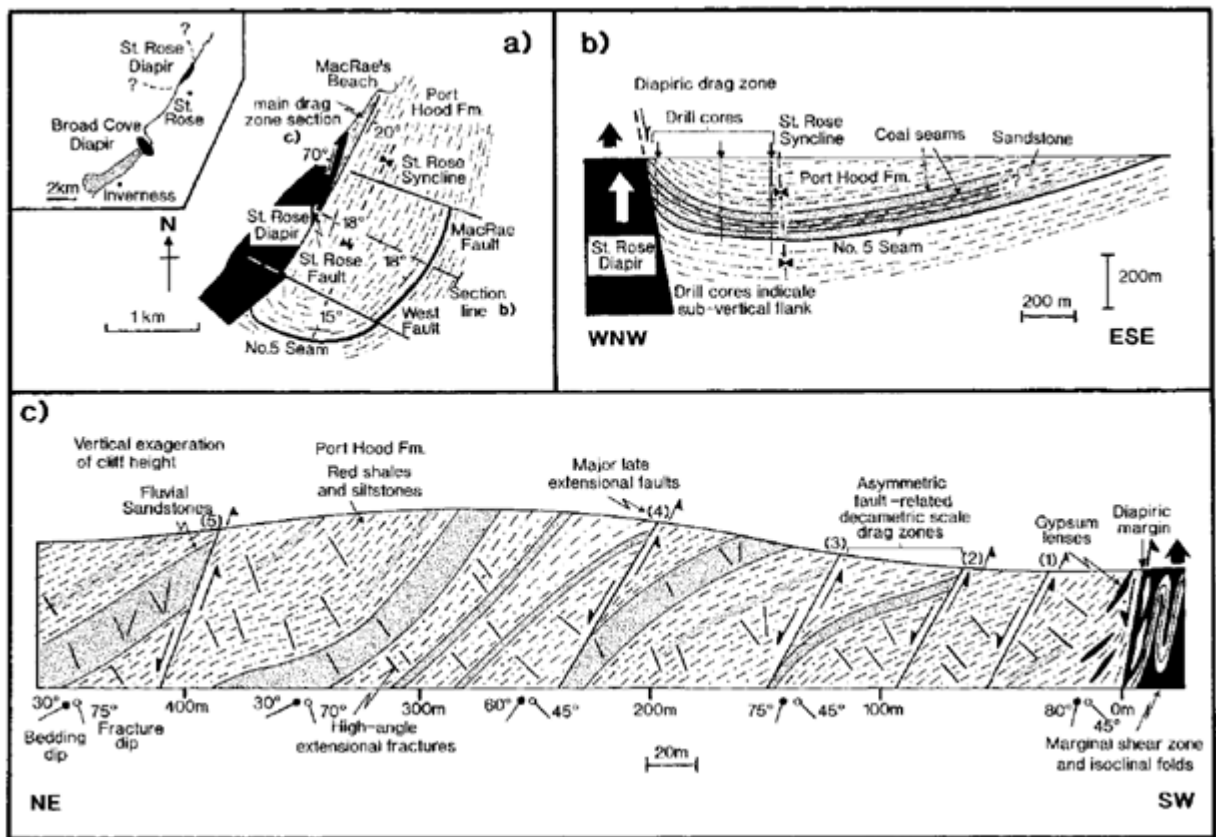


Figure 32 – St Rose Diapir map and sections from Alsop et al. (2000). A) The map highlights position of upturned section. B) WNW-ESE section showing overall geometry of St Rose Diapir based on outcrop and coal drill core data. C) NE-SW section through St Rose upturned zone showing rotation of shales and sandstones of Port Hood Fm.

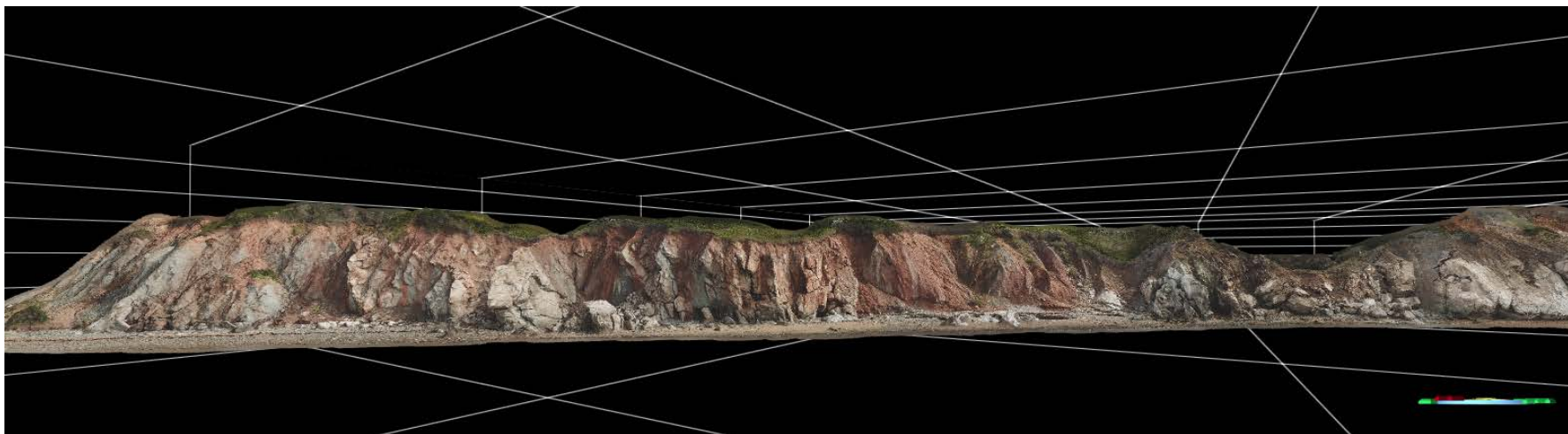


Figure 33a – St Rose diapir – northern part of section (Courtesy of Jack Richardson). North is left of section.

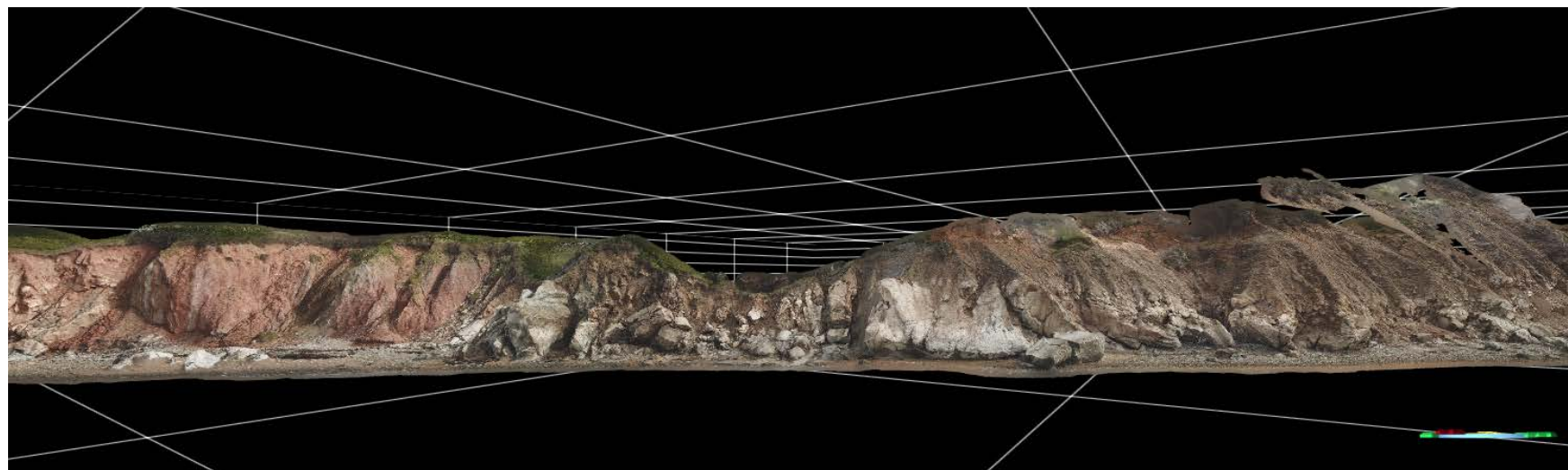


Figure 33b – St Rose Diapir – southern part of section (Courtesy of Jack Richardson). South is right of section.

Summary of Outcrop Evidence to Support Diapirism

1. Abundant extensional normal faults (with only occasional thrust faults) throughout the sequence of upturned stratigraphic units in upturned zones.
2. Convergent bedding patterns within diapiric upturned zones.
3. Discordant brecciated contacts at the evaporite margins with more rigid lithologies (sandstones, conglomerates, limestones).
4. Refolded folds, vertical / steeply plunging fold hinges and strong prolate (constrictional) strains producing L fabrics in the evaporites.
5. Unconformities within the Inverness Formation indicate diapiric growth during deposition of this formation.
6. Evidence of diapirism in surrounding sedimentary basins determined from well and seismic data.

Upturned zone	Width	Strata in upturned zone at surface	Overburden competency and contrast	Timing of major diapirism	Structures and deformation conditions	Geometry of upturned profile
Broad Cove	500 m	Hastings Fm.; shale, thin sandstone; Broad Cove Fin. on SW margin	Competent; sub-homogeneous (little lithological contrast)	post Namurian and pre Stephanian?	Early high-angle fractures throughout upturned zone. Late-extensional faults separate high-strain inner upturned zone	Broad gentle upturned profile transected by late faults
St. Rose (not visited on this trip)	450 m	Port Hood Fm.; channel sandstone, shale	Competent; moderately heterogeneous	post Westphalian A	Early high-angle fractures throughout upturned zone. Late-extensional faults segment upturned zone; granulation seams in sandstones	Broad gentle upturned profile segmented by late faults
Finlay Point	300 m	Unnamed red conglomerate; Inverness Fm.; shale, coal, thin sandstone	Moderate competence; heterogeneous	post Westphalian C/D - Stephanian	Early high-angle fractures throughout upturned zone. Late-extensional faults separate high-strain inner upturned zone. Bedding-parallel slip in weak horizons	Moderately broad gentle upturned profile markedly segmented by late faults
Coal Mine Point	250 m	Inverness Fm.; shale, coal and channel sandstone	Low-moderate competence; highly heterogeneous	post Westphalian C/D - Stephanian	Granulation seams and fractures in sandstones adjacent to diapir, but few in more distant sandstones; Marked bedding-parallel slip in weak horizons	Moderately narrow upturned profile which is pronounced adjacent to the diapir
Port Hood Island	70 m	Henry Island Fm.; conglomerate, sandstone, shale	Low competence; relatively homogeneous	Namurian - Westphalian B/C or later?	Faults and fractures rare, due to minimal lithification during diapir downbuilding. Rotated unconformity in upturned zone. Sedimentation indicates diapir created topography	Extremely narrow and pronounced upturned profile. Absence of major faults

Figure 34 – Summary of Cape Breton upturned zones

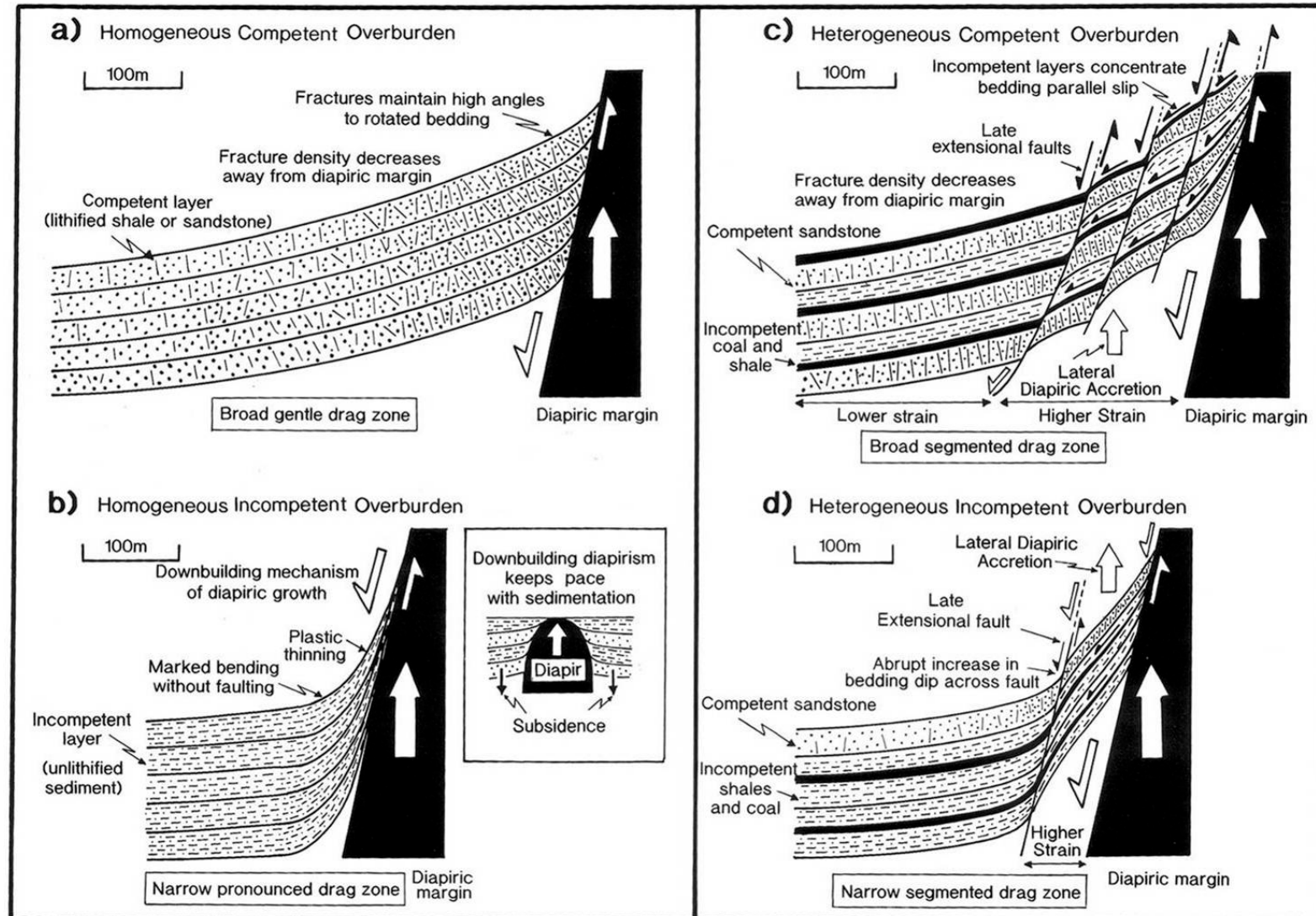


Figure 35 – Schematic diagrams of diapir upturned profiles, summarising type section geometries and deformation mechanisms (Alsop et al. 2000)

References

- Alsop, G.I., Brown, J.P., Davison, I. and Gibling, M.R., 2000. The geometry of upturned zones adjacent to salt diapirs. *Journal of the Geological Society, London*. Vol. 157 pp 1019-1029.
- Boechner, R.C., 1986. Salt and potash resource in Nova Scotia. *Department of Mines and Energy Bulletin*, 5. Halifax, Nova Scotia.
- Brown, J.P., 1998. Deformation and sedimentation adjacent to Carboniferous diapiric salt structures, Nova Scotia. PhD thesis, Dalhousie University, Halifax, Nova Scotia.
- Giles P.S., and Boechner, R.C., 1982. Subdivision and regional correlation of strata of the Upper Windsor Group, Cape Breton Island and central Nova Scotia *Department of Mines and Energy Report 82-1*, pp 69-78.
- Gibbling, M, Culshaw, N. Rygel, N.C. Pascucci, V. 2008. The Chapter 6: The Maritimes Basin of Atlantic Canada: Basin Creation and Destruction in the Collisional Zone of Pangea. In *Sedimentary Basins of the World*.v. 5 211-244.
- Howie, R.D. and Barss, M.S., 1975. Upper Palaeozoic rocks of the Atlantic Provinces, Gulf of St Lawrence and adjacent continental shelf. In: *Offshore Geology of Eastern Canada*. Geological Survey of Canada. Paper 74-30, pp 35-50.
- Raesian R., and Tizzard, A., 2015. Basement-cover relations in the southeastern Cape Breton Highlands, Nova Scotia Canada. *Atlantic Geology*, 51, <https://journals.lib.unb.ca/index.php/ag/article/view/22029/28009>
- Rowan, M., Lawton, T.F., Giles, K.A., et al. 2003. Near salt deformation in La Popa Basin, Mexico, and the northern Gulf of Mexico: a general model for passive diapirism. *Bulletin American Association Petroleum Geologists*, 87, 733-756.

CONJUGATE MARGINS CONFERENCE 2018

Celebrating 10 years of the CMC: Pushing the Boundaries of Knowledge



SPONSORS & SUPPORTERS

Diamond \$15,000+



Platinum \$10,000 – \$14,999



Gold \$6,000 – \$9,999 & In-Kind



AAPG
Canada Region

bp



Bronze \$2,000 – \$3,999 & In-Kind



DALHOUSIE
UNIVERSITY

1818
2018



Basin & Reservoir Lab

Patrons & Supporters \$1,000 – \$1,999 & In-Kind



North Africa Research Group
www.narg.org.uk



CANADA-NOVA SCOTIA
OFFSHORE PETROLEUM BOARD



Natural Resources
Canada / Ressources naturelles
Canada

Canada

Dalhousie

University,

Halifax,

NOVA

Scotia,

August

19–22,

2018