Chapter 5 - Structure and Basin Development

Introduction

The most significant structural features that influenced the Cumberland Basin are: (1) the Cobequid - Chedabucto Fault System (Minas Geofracture), (2) the North Fault (Keppie, 1976) along the northern margin of the Cobequid Highlands Massif, and (3) the Cumberland Basin and its internal structures (Fig. 5-1). In this chapter these structural features are examined and their origins are inferred to reconstruct the tectonic and resultant sedimentological history of the Cumberland Basin.

Cobequid - Chedabucto Fault System

Location and Displacement

The Cobequid - Chedabucto Fault System (Minas Geofracture) is an east-west series of faults (Fig. 5-2) with a complex movement history. The Cobequid - Chedabucto Fault System separates the Meguma Terrane from the Avalon Terrane in northern Nova Scotia (Donohoe and Wallace, 1985). The on-land trace of the fault system is over 300 km long (Mawer and White, 1987), from Chedabucto Bay in the east to Chignecto Bay in the west. To the west beneath the Bay of Fundy the Cobequid - Chedabucto Fault System curves to a southwesterly trend, changes to a complex flower structure (Nance, 1988), and is linked with convergent thrust faulting and metamorphism in southern New Brunswick. The structure is further complicated in the Bay of Fundy area by the superimposed Mesozoic Fundy Rift and by northeast-trending regional faults in southern and south-central New Brunswick. To the east the fault system is similarly complicated by the Mesozoic Orpheus Graben extending eastward from Chedabucto Bay.

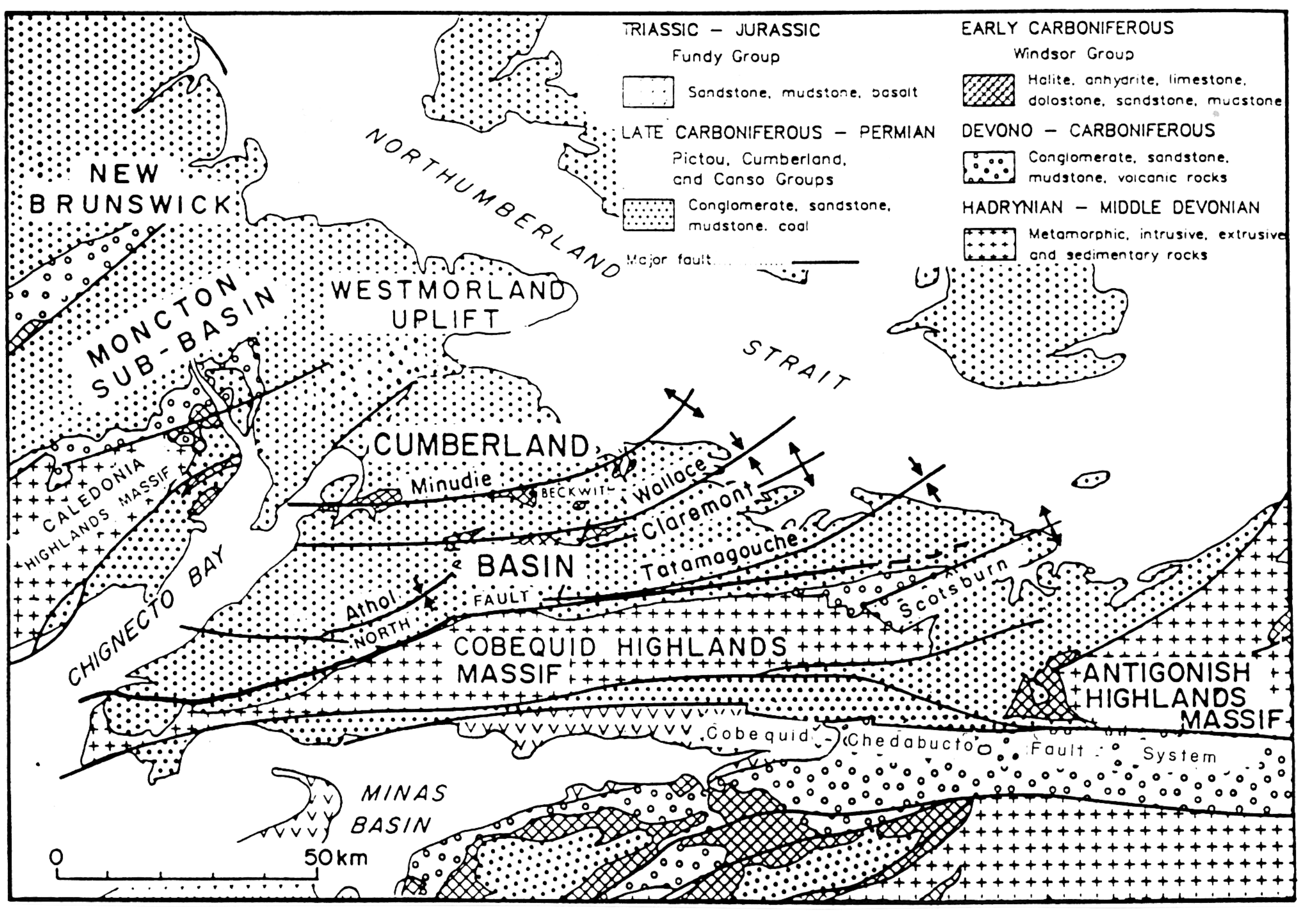


Figure 5-1. Location map of major structures in the Cumberland Basin.

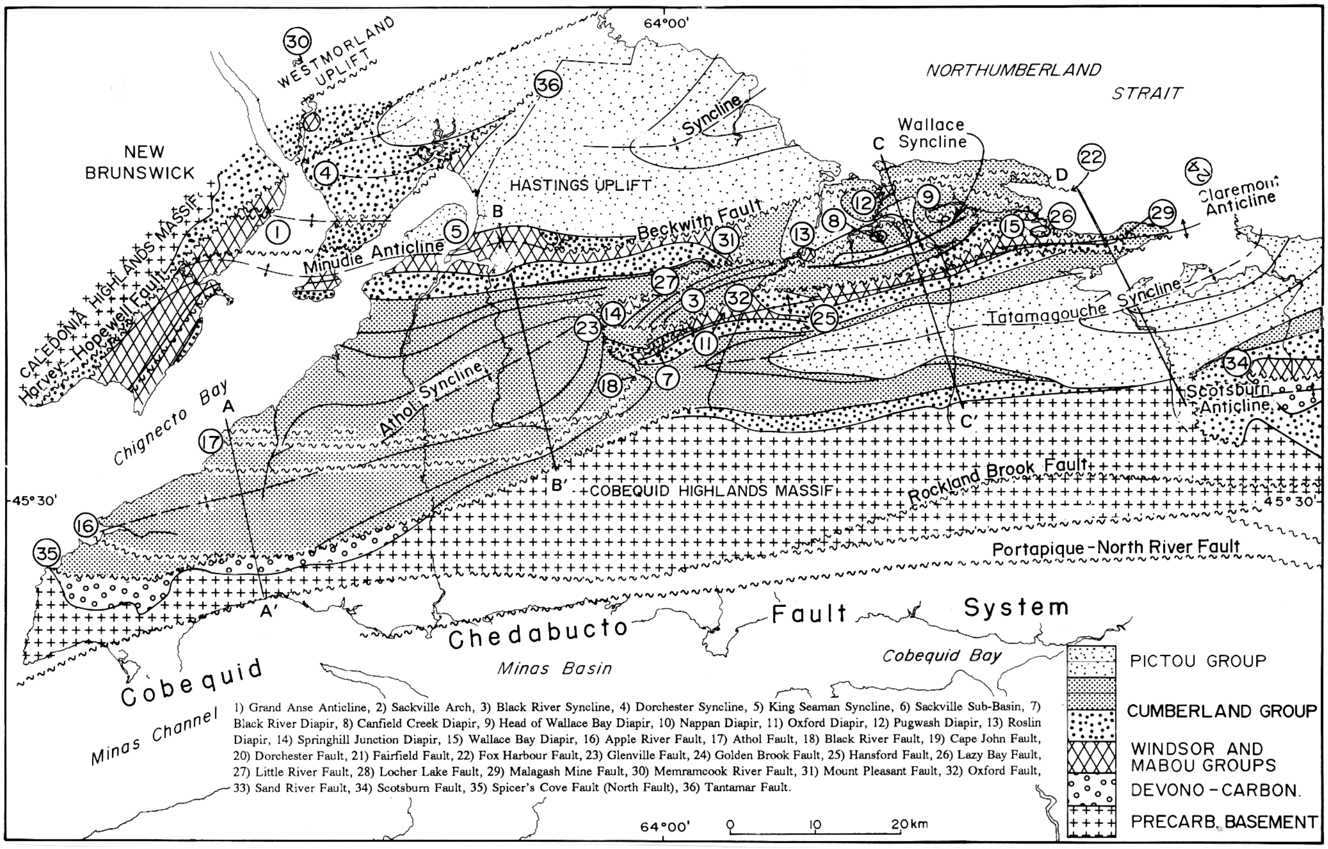


Figure 5-2. Location map of structural features in the Cumberland Basin area.

Individual faults within the system have been described as having normal, reverse, dextral, or sinistral displacement (Eisbacher, 1969; Keppie, 1982a; Mawer and White, 1987). Mawer and White (1987) concluded that displacements are expected to vary within a strike-slip fault zone. Most of the workers in the last thirty years have suggested that the Cobequid - Chedabucto Fault System is a strike-slip movement zone (Eisbacher, 1969; Webb, 1969; Bradley, 1982; Keppie, 1982a; Donohoe and Wallace, 1985; Mawer and White, 1987), whereas earlier workers such as Bell (1944, 1958) suggested that normal faulting occurred along the fault zone at the basin margins. Net dip-slip movement probably occurred along the faults, as indicated by basin margin fanglomerate deposit; however, these movements may have been relatively minor in comparison to the interpreted strike-slip displacements.

Keppie (1982a) suggested that the fault system had a complete reversal in displacement sense from dextral to sinistral strike-slip movement in the Mesozoic. Mawer and White (1987), on the basis of their research of microstructures in the fault zone at either end of the on-land trace, concluded that the fault zone had a protracted history of dextral strike-slip movement, but no evidence for major sinistral movement was documented. Yeo and Ruixiang (1986) and Fralick and Schenk (1981), based on structural and sedimentological studies in and adjacent to the Hollow and the Cobequid faults in the Stellarton area, concluded that these faults underwent dextral offset. The Hollow and the Cobequid faults are both related to the Cobequid - Chedabucto Fault System.

The amount of displacement along the fault zone is not well documented. Donohoe and Wallace (1985) suggested dextral offset of 20 to 85 km on the system along the Cobequid Highlands Massif, based on the offset of rhyolitic and granitic rocks on either side of the fault zone. Keppie (pers. comm.) suggests that the dextral offset may be as much as 200 km, based on the occurrence of Torbrook Formation clasts in Middle Devonian rocks. These clasts, occurring in strata near Chedabucto Bay at the eastern end of the on-land trace of the fault system, are 200 km east of the nearest Torbrook Formation outcrops south of the fault zone.

Timing of Fault Movements

Fault movements along the Cobequid - Chedabucto Fault System are interpreted as having begun by the Middle Devonian or earlier (Schenk, 1971; Keppie, 1982a; Donohoe and Wallace, 1985), and continuing intermittently (recorded locally by deposition of coarse sediments) throughout the Carboniferous (Donohoe and Wallace, 1985; Yeo and Ruixiang, 1986; Ryan *et al.*, 1987). Donohoe and Wallace (1985) and Ryan *et al.* (1987) estimated that the net dip-slip movements along the fault zone occurred in the Namurian and early Westphalian (Fig. 5-3) as indicated by the presence of thick fanglomerate deposits adjacent to the faults. These dip-slip movements may have occurred without any associated strike-slip movements or, more likely, as a component of the strike-slip displacement (Donohoe and Wallace, 1985). The presence of fanglomerates constrains the timing of tectonic events within the Maritimes Basin and aids in the modelling of basin evolution (cf. Fralick and Schenck, 1981; Yeo and Ruixiang, 1986; Ryan *et al.*, 1987). Additional discussion of the timing and other implications of fault movements will be integrated into the basin evolution section of this chapter.

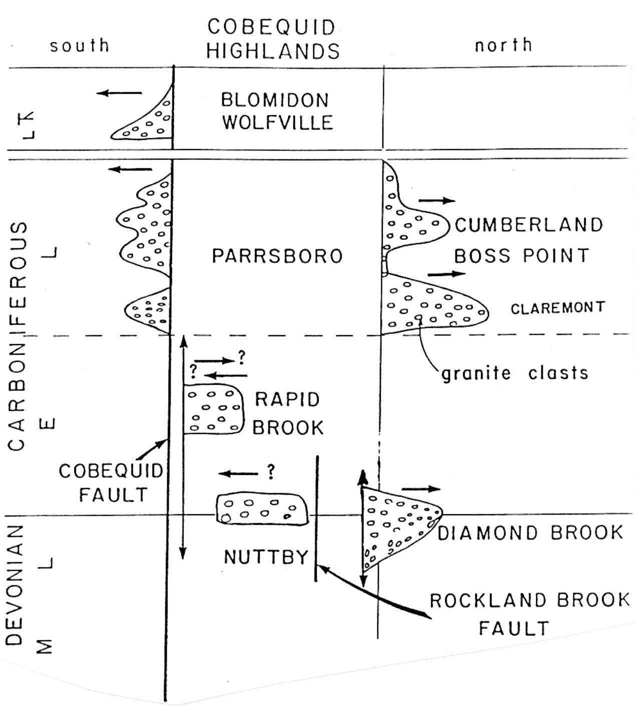


Figure 5-3. Conglomerate units on the north and south side of the Cobequid Highlands Massif.

North Fault

Location and Displacement

The term "North Fault" was introduced by Keppie (1976) to define the fault zone (including the Spicers Cove Fault) on the northern flank of the Cobequid Highlands Massif (Fig. 5-1). The fault system forms part of the southern boundary of the Cumberland Basin. The on-land fault trace is locally overlapped by Upper Carboniferous rocks (i.e. south limb of the Tatamagouche Syncline; Fig. 5-4, Section D-D[1]) and at other places it clearly displaces rocks of similar age, indicating a complex movement history. The fault zone appears as lineaments on radar images and extends from River Philip to Earltown (Keppie, 1976). The zone can be traced in the subsurface as far east as River John (Fig. 5-4) using seismic profiles, aeromagnetic maps and gravity maps. The area between Rodney and West-chester Station has very limited outcrop and the North Fault is inferred (Fig. 5-4) from seismic data and remote sensing. West of River Philip, the fault system is apparently represented by the Spicers Cove Fault as well as the Athol, Sand River and Sand Cove faults in the west-central part of the Athol Syncline. Detailed interrelationships between these faults are not clearly understood. Keppie (1976) concluded that the irregular configuration in the west was due in part to overstepping Upper Carboniferous cover south of the fault trace. He suggested that there must have been a Late Carboniferous to Permian reactivation of the fault which accounted for the presence of the lineation in Carboniferous cover rocks. Field mapping in the western part of the basin indicates that the fault is not overlapped by Upper Carboniferous strata and the fault at surface separates Devonian (or possibly Early Carboniferous) conglomerate on the south from Upper Carboniferous strata north of the fault. Moderate to shallow dips on the fault, thick glacial cover, and cross-faulting may account for the more irregular trace of the fault. Seismic lines that transect this fault are interpreted by Chevron Standard (Nantais, pers. comm.) as indicating a thrust component. Although older strata may overlie the Upper Carboniferous basin-fill units at some localities along the fault, a low angle ($<45°$) strike-slip displacement could also result in a similar configuration of the strata (Fig. 5-4).

Most of the seismic data for the area are unavailable for publication. Insights into the nature of faults along

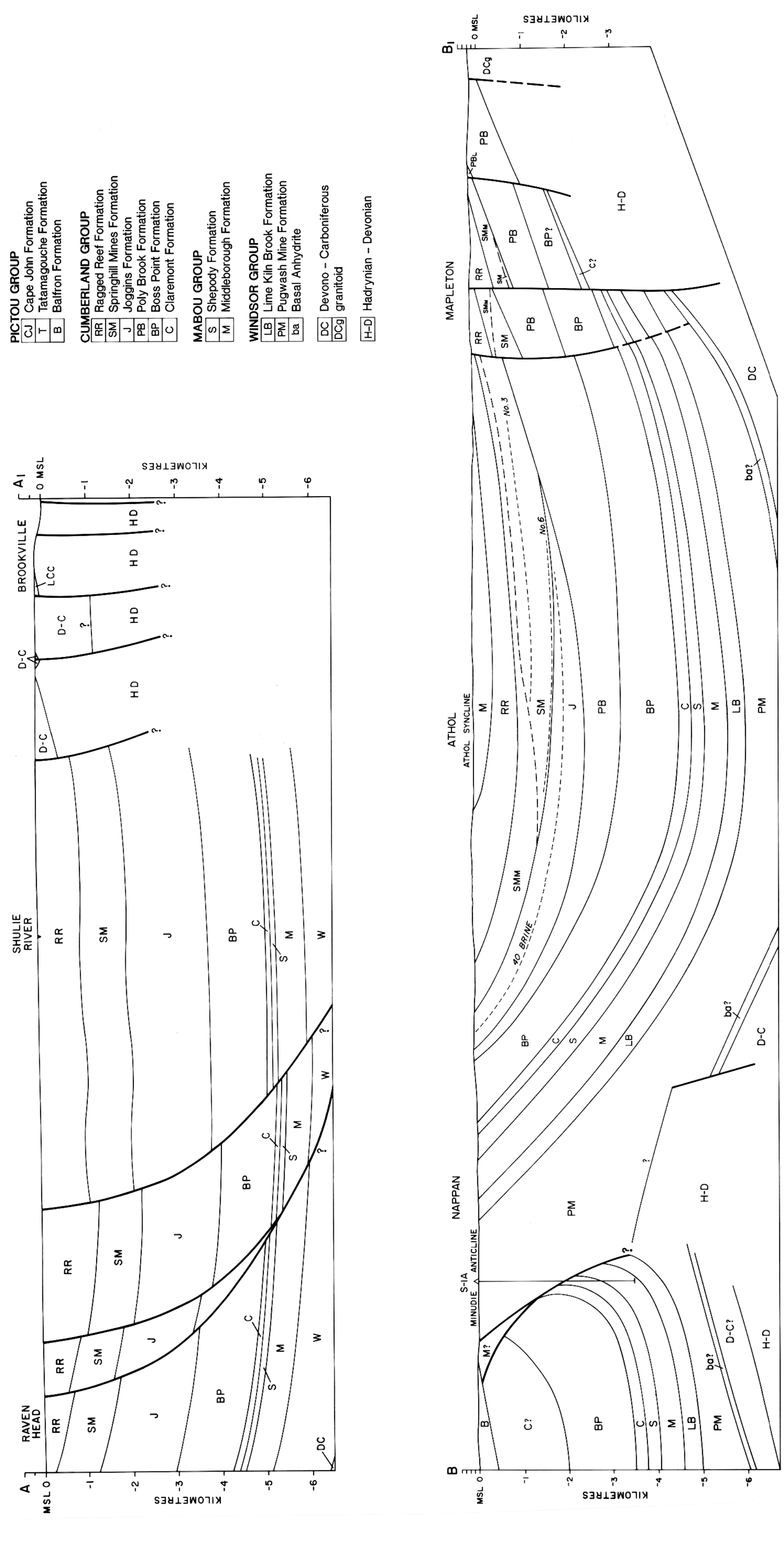


Figure 5-4. Cross-sections for the Cumberland Basin after Ryan *et al.*, 1990; for locations see Figure 5-2.

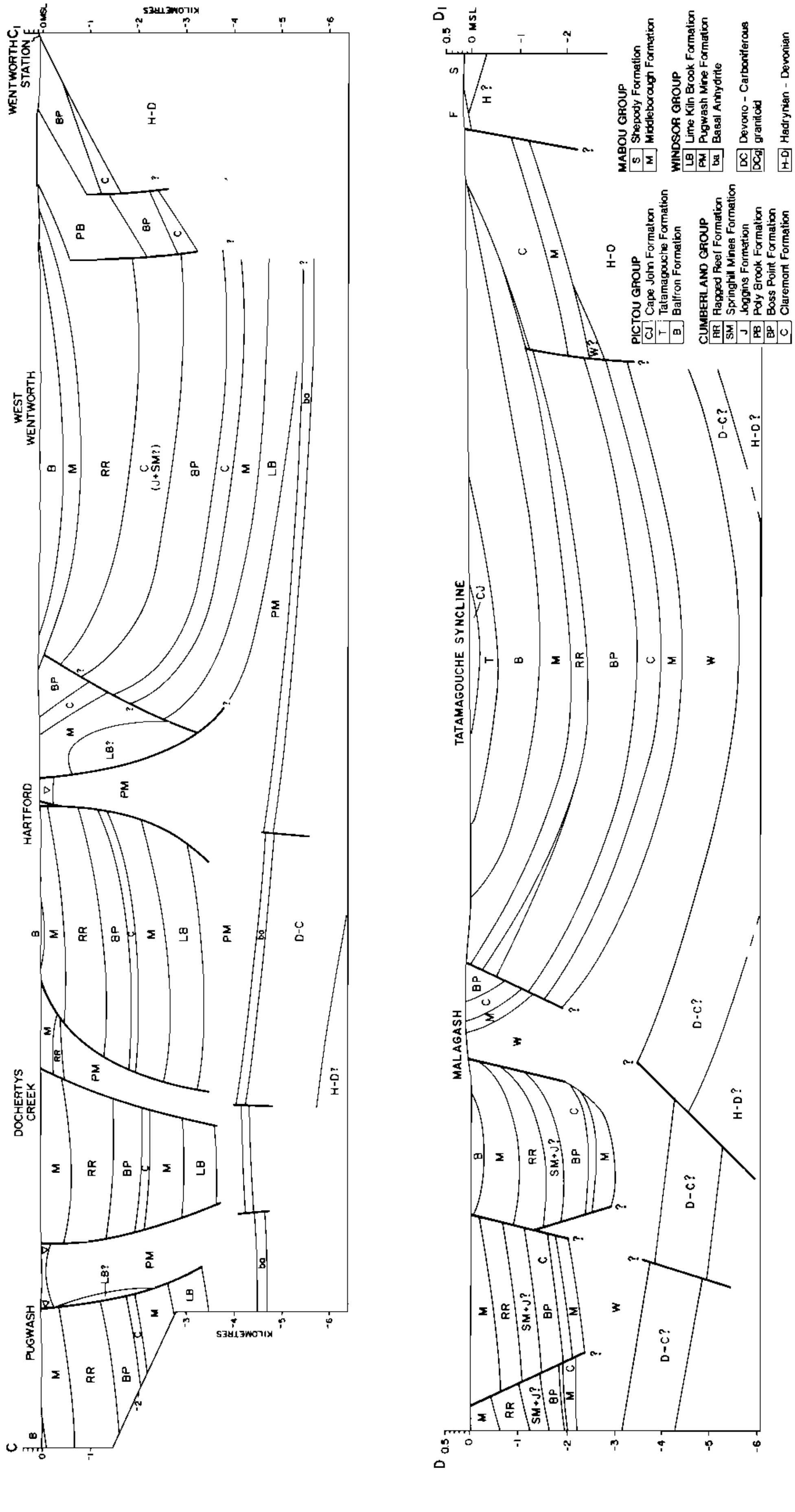


Figure 5-4. (cont.) Cross-sections for the Cumberland Basin after Ryan *et al.*, 1990; for locations see Figure 5-2.

the Cumberland Basin margins based on these data, as well as from the Geological Survey of Canada seismic data are incorporated into geological cross-sections in Figure 5-4. In the western part of the Cumberland Basin it is clear that the North Fault is not one fault occurring in isolation but is a composite of numerous splays that displace Upper Carboniferous strata in the basin. The nature and location of these associated faults will be discussed in the section of this chapter on the Cumberland Basin structures. The North Fault is parallel to the Cobequid - Chedabucto Fault System and major internal structures of the Cumberland Basin, including the Athol - Sand Cove - Sand River fault set and the faulted Minudie and Claremont anticlines. These fault sets and the Spicers Cove and Apple River faults probably have a similar sense of displacement and were genetically related.

Within the Cumberland Basin proper there are several significant faults and/or fault sets that are not apparently related to evaporite tectonics, although locally they may be conduits for saline brines (i.e. in South Athol drillhole 88-1). The three most significant faults include: (1) the Sand Cove - Sand River fault, (2) the Athol Fault, and (3) the Apple River Fault. All three of these faults are in the western part of the Cumberland Basin and are oriented east-west. These faults converge in the structurally disrupted area of Springhill and Rodney and are splays of the North Fault (Spicers Cove Fault), which forms the southern boundary of the basin in the west. The faults are exposed in outcrop along the shores of Chignecto Bay as zones of high-angle reverse faulting (Figs. 5-2, 5-4). Normal faults also occur within the fault zones, although the majority of slickenside surfaces indicate sub-horizontal movement. Utilizing seismic data for the western part of the basin, Calder and Bromley (1988) interpreted these structures as high-angle faults to depth. Chevron Standard seismic interpretations and those of Ryan and Boehner (1988) suggest that these structures are listric and they are interpreted to shallow significantly at depth toward the south (Fig. 5-4). The orientation, proximity to the North Fault, and the strike-slip nature of displacement suggest that these faults probably formed in response to movement along the North and Cobequid faults during the late Westphalian.

Waldron *et al.* (1989) described pre-Cumberland Group (Namurian-Westphalian A) northward overthrust structures in mylonitic zones in the western part of the Cobequid Highlands. They related the structures to convergent tectonics along portions of the Cobequid - Chedabucto Fault System. These ductile structures were apparently overprinted by later brittle faults probably of Mesozoic age.

A similar thrust setting may be inferred in the complete Scotsburn Anticline area at the eastern end of the Cobequid Highlands. The occurrence of Middle Devonian strata (Fountain Lake Group) overlying redbed strata of the Middleborough Formation (Viséan) indicates an overthrust relationship. The presence of Claremont Formation (Namurian) rocks resting with angular conformity on both rock units suggests that a structural event took place before the late Namurian.

Timing of Displacement

Ryan *et al.* (1987) examined the timing of fanglomerate deposition on the Cobequid and North faults and suggested that the timing of net dip-slip movements on each of the faults was almost identical (Fig. 5-3), with the major movements taking place in the Namurian and early Westphalian. Subsequent displacement of the Upper Carboniferous strata indicates that post-Carboniferous (Permian to possibly Mesozoic) movement has also occurred and affected the structure within the basin (Fig. 5-4).

In the Tatamagouche area of the eastern Cumberland Basin, dips of the older strata along the southern margin of the basin adjacent to the Cobequids are approximately 25-35°. The younger Pictou Group strata have dips of only 5-15° at the same relative position to the fault trace. This angular discordance indicates that net dip-slip movement occurred in the east during the early Westphalian, even though early Westphalian fanglomerate deposition did not occur in that area.

The Cumberland Basin

Introduction

The Cumberland Basin is defined as being the basin that lies between the Cobequid Highlands Massif and the Caledonia Highlands. The basin has the general internal configuration of a synclinorium composed of a series of prominent synclines, the Athol, Scotsburn, Tatamagouche, Wallace and Amherst synclines, and two major diapiric anticlines, the Minudie and Claremont (Malagash) anticlines. Structural features within the basin can be broadly related to: (1) salt structures, including diapirs, domes, diapiric anticlines, and folds and faults related to salt flow; (2) basin development (growth) features unrelated or indirectly related to evaporite tectonics, including growth faults, strike-slip faults and major synclines; and (3) structures related to buried uplift blocks (e.g. Hastings Uplift), including joint, and thrust faults (Fig. 5-2).

Salt Structures

The Windsor Group evaporitic sequence varies in degree of deformation throughout the Maritimes Basin. Boehner (1986) classified the deformation of evaporites in the Cumberland Basin as Type D (Fig. 5-5): evaporitic sequences that exhibit an extreme intrusion-diapiric character, active tectonic role, abundant salt and thick basin fill accompanying rapid subsidence. All of these elements probably occurred within a rapidly subsiding mobile basin. The evaporites of the Cumberland Basin deformed to create diapiric anticlines, salt walls to salt stocks, or an aligned series of isolated diapiric salt stocks (domes). Terms used to describe the morphology of diapiric structures within the basin conform to the classifications proposed by Trusheim (1960) and as modified by Talbot and Jackson (1987).

Diapiric Anticlines

The two major diapiric anticlines within the Cumberland Basin of northern Nova Scotia are: (1) the Claremont (Malagash) Anticline, and (2) the Minudie Anticline (Fig. 5-1). The Claremont Anticline is a 100 km long east-west feature with outcrops of Windsor Group rocks exposed locally along the anticlinal axis at Springhill, Claremont, Oxford, Hansford, and Malagash (Fig. 5-6). The Minudie Anticline is an east-west structure that extends for 60 km westward from southern New Brunswick through Minudie and Nappan to (at least) Beckwith in the east (Fig. 5-6). The Pugwash diapir lies along the same trend and probably represents an extension of this structure.

The anticlines are evaporite cored, fault controlled, and formed by salt and anhydrite diapirism. Seismic and geological cross-sections through these features (Howie, 1988; Boehner, 1986) indicate that they occur as salt walls or stocks which are aligned east-west, parallel with, and probably genetically related to the Cobequid - Chedabucto Fault System.

Isolated Domes

Isolated evaporite domes, or salt stocks occur at: (1) Black River, (2) Roslin, (3) Canfield Creek, and (4) Wallace Bay (Fig. 5-6). Evaporite domes in the complex Wallace Syncline are aligned east-west, parallel to the two major diapiric anticlines. This alignment strongly indicates a genetic link to intrusion along faults within the Wallace Syncline.

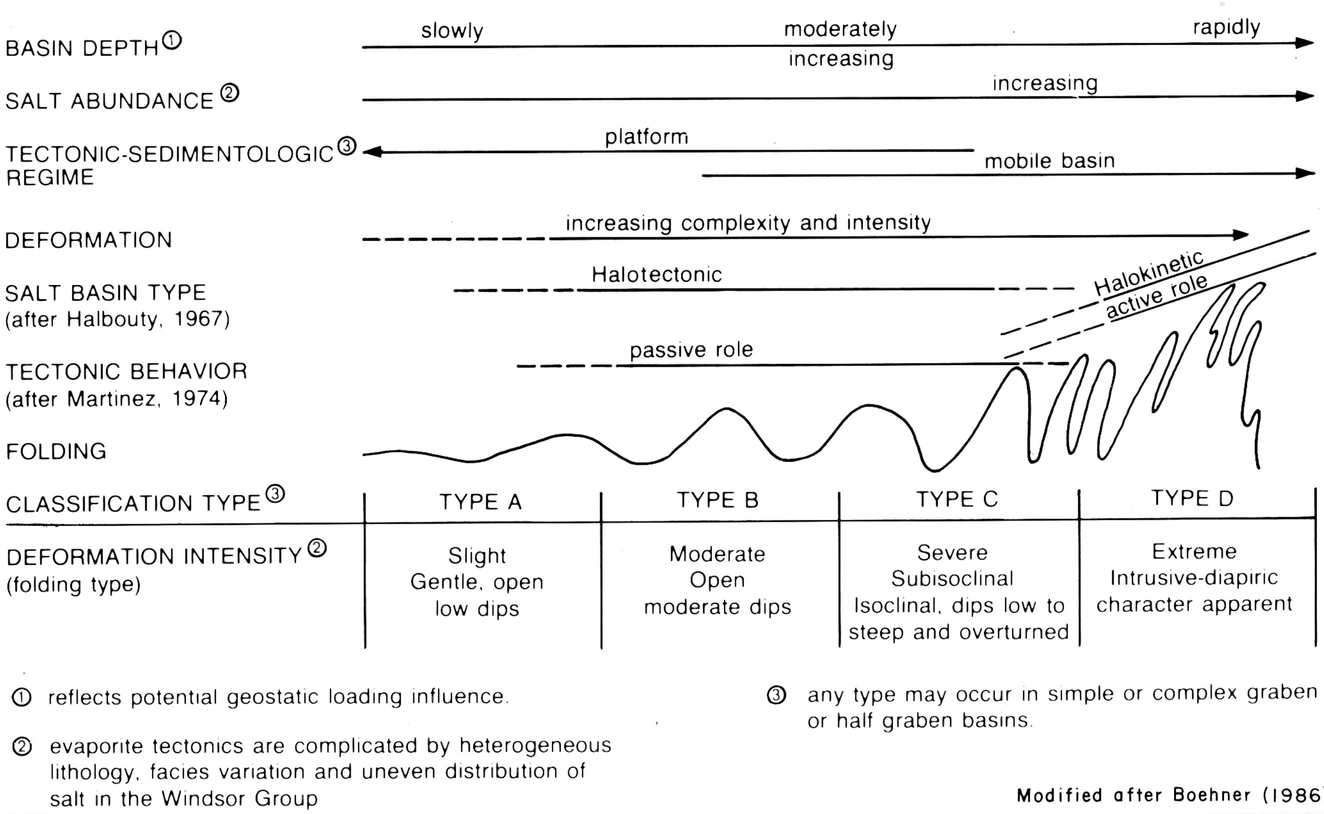


Figure 5-5. Structural classification of evaporite structures in Nova Scotia (after Boehner, 1986).

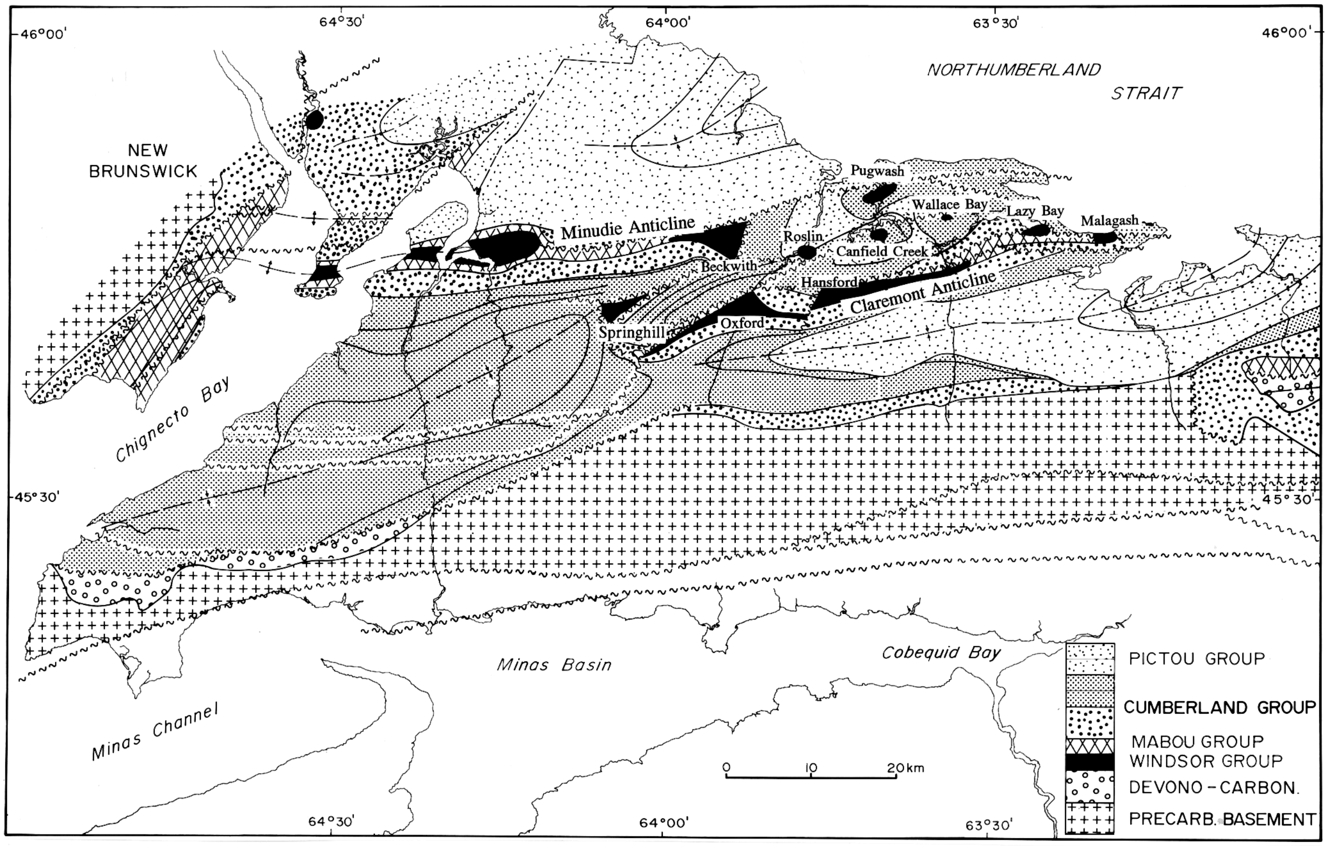


Figure 5-6. Location map of diapiric anticlines and isolated salt-cored domes.

The Windsor Group outcrop areas of these structures are limited and typically sub-circular, ranging from one to several kilometres in diameter. The Roslin structure is the only dome in which a salt core has been confirmed by drilling; however, gypsum occurs as outcrop and in shallow drillholes that have intersected highly disrupted, karst evaporite (solution collapse-residual caprock) at all of the domes.

Emplacement and Timing of Diapirism

Two apparently conflicting theories have been proposed for the timing of diapirism within the Cumberland Basin. Van de Poll (1972) and Calder (1981) both suggested that brittle deformation adjacent to the diapirs indicates a post-Pictou/Cumberland Group emplacement. Bell (1944) implies that the angular unconformities between the various Upper Carboniferous formations and groups, in the anticlinal and domal areas of the basin, are evidence for syndepositional diapirism during the Late Carboniferous. Ryan (1985) also favoured a syndepositional diapirism model, based on divergent paleocurrent data away from the areas of domes and anticlines. Williams (1974) concluded, from thinning of units adjacent to the diapirs in seismic profiles, that diapirism must have been syndepositional. The angular unconformity exposed at the Dewar Hill Quarry, near Pugwash, has flat-lying Malagash Formation strata overlying overturned Windsor Group carbonates and redbeds. It is probably the most convincing evidence for syndepositional (mid-Westphalian) tectonism and evaporite diapirism found within the basin (Fig. 4-3).

These two theories (syn- and post-Westphalian diapirism) are not necessarily mutually exclusive. Although initiated and most significant during the Carboniferous, diapirism may have continued periodically through the late Carboniferous, for some time after the Carboniferous (Permian?), and perhaps again in the Mesozoic. Talbot and Jackson (1987) suggest that diapirism in the Gulf Coast region of the United States was a prolonged event which may be still continuing at the present time. Progressive evaporite tectonics that evolve into a diapiric phase over an extended period of time supply an appealing explanation for the dichotomy of structural and sedimentological features found within the

Cumberland Basin. In addition, post-Cumberland Group strike-slip offset and the possibility of high-angle reverse to possible thrust termination of the east-west faults near Springhill Junction may explain the juxtaposition of Windsor Group diapiric evaporites with the Springhill Mines Formation in a brittle deformation setting.

The pronounced east-west orientations of diapiric structures within the basin are parallel to the Cobequid and the North Fault systems and suggest that these faults were preferred sites of evaporite tectonics and diapirism. The nature and movement history of these faults is unclear; however, their similar orientation to that of the Cobequid and North Faults suggests that displacements may also have been strike-slip in nature. Several major east-west faults related to diapirs in the Wallace Syncline and to the northern border of the Claremont Anticline converge at the western apex of the Athol Syncline in the Springhill area. One set converges in a poorly defined diapiric structure near Springhill Junction to the north. The other faults converge in the area near Black River and Salt Springs characterized by rotated fault blocks and reoriented faults (to northeast trends) at the termination of the Claremont Anticline. Based on stratigraphic displacements a significant dextral offset may be inferred along these fault zones which are located south of the Minudie Anticline and probably extend eastward through the Wallace Syncline as far as Wallace Bay.

Springhill Area

Calder (1984b, and in Boehner *et al.*, 1986) described the structure in the axial area of the Springhill Anticline based upon extensive diamond-drill information and detailed mapping in the Rodney Open Pit. The gently plunging axis of the anticline is complicated by block faulting in a series of major curvilinear faults that define a semiradial pattern complicated by cross faults. Several sets of faults were recognized, with early-stage major normal faults (synthetic and antithetic cross-fault sets) and strike-slip or scissors faults that were succeeded by later bedding-plane and thrust faults. Evaporite tectonism was believed to have post-dated deposition of the Cumberland Group coal measures at Springhill as they were brittly deformed in areas where they were in close proximity to the evaporite structures.

The Black River Syncline may be a block resulting from oblique strike-slip faulting which has apparently repeated (perhaps by lateral telescoping) a portion of the southern limb of the Minudie Anticline. The western extension of these faults into the Athol Syncline is problematical; there is no apparent evidence for major faults disrupting the syncline. The faults may terminate, however, and the inferred strike-slip movement may be accommodated in a complex reverse or overthrust diapiric structure along the western side of the Athol Syncline (Fig. 5-4).

The western termination of the Claremont Anticline and related faults against the Athol Syncline near Springhill, is similarly abrupt, structurally complex and perhaps may also be related to continuation of the reverse or overthrust structure. Faults related to the Claremont Anticline, however, may continue to the southwest and converge with splays of the North Fault near Leamington and Rodney. This type of complex structure is generally similar to the western termination of the Minudie Anticline in southern New Brunswick. Reed (1992) suggested that the present configuration of the Springhill Anticline resulted from the combined effects of initial, dextral transpression along the Athol - Sand Cove fault zone, which produced the southwest-plunging fold, and later sinistral transtension, which resulted in the development of normal faults and graben structures across the crest of the fold.

The extent and termination style of the east-west Minudie Anticline to the west is not well understood. The western extension of the Cumberland Basin terminates in a complex faulted area on the southeast border of the Caledonia Highlands Massif in southern New Brunswick. Basin structure is reoriented from the prominent east-west trend to the regional trend of northeast-southwest. This is reflected not only in the basement highland blocks, but also in the parallel major faults including the Harvey-Hopwell and Locher Lake faults. The Minudie Anticline (and related faults) apparently terminates in the area of Shepody Bay into a complex of splays, thrusts (especially at or near convergent or restraining bends) and subordinate folds with evaporite tectonism including diapirism. These types of structures and the general tectonic setting may be analogous to the complex flower structure at the termination (possibly reorientation) of the Cobequid - Chedabucto Fault System in the Bay of Fundy and southern New Brunswick described by Nance (1988). Reed (1992) suggested that the Athol - Sand Cove fault zone exposed at Clam Cove represents a negative flower structure.

Bell (1958) was the first to link the orientation of post-Mabou (Canso or Riversdale group) faults to the distribution of diapiric structures. Howie and Cumming (1963) also suggested that fault zones may have controlled evaporite distribution in the Maritimes Basin. Bell (1958) suggested that diapirism began at these areas of weakness and was subsequently driven by the confining pressures of the accumulating sediments, thus linking coal basin development in the western part of the basin with evaporite tectonics and diapirism. Bidgood (1970) indicated, based on seismic and gravity geophysical data, that the salt structures of the Claremont Anticline are fault controlled. Bidgood (1970) and Howie (1986) indicated that basement faulting occurred beneath areas of diapirism based on the seismic profiles available. The mechanisms of fault-controlled diapirism have been demonstrated experimentally by Lemon (1985). Structures created during modelling by Lemon (1985) are very similar to those observed in the diapiric anticlines of the Cumberland Basin.

Areas removed from the diapiric anticlines and domes, and the Cobequid Fault and North Fault, are relatively simple structurally. Williams (1974) suggested an evaporite removal mechanism for the formation of synclines and anticlines in the southern Maritimes Basin. Ryan (1985) supported this hypothesis and indicated that the Tatamagouche Syncline and the Claremont Anticline are genetically related structures caused by evaporite removal in areas where there was rapid sedimentation, and diapirism in areas of lesser confining pressures. This simplistic hypothesis is possible. However, halokinesis alone cannot explain the initiation of diapirism in the basin. A tectonically driven (halotectonic) mechanism for the initiation of diapirism is favoured, rather than a gravity driven halokinetic mechanism (Trusheim, 1960), because many other thick sequences of evaporites elsewhere in the world, with similar thicknesses of overlying strata, are undisturbed (Kingston *et al.* 1983). It would seem that gravity alone is unlikely to overcome the inertia, although only slight tectonic forces may be necessary to initiate salt flow (Talbot and Jackson, 1987).

Folds and Faults Related to Evaporite Tectonics

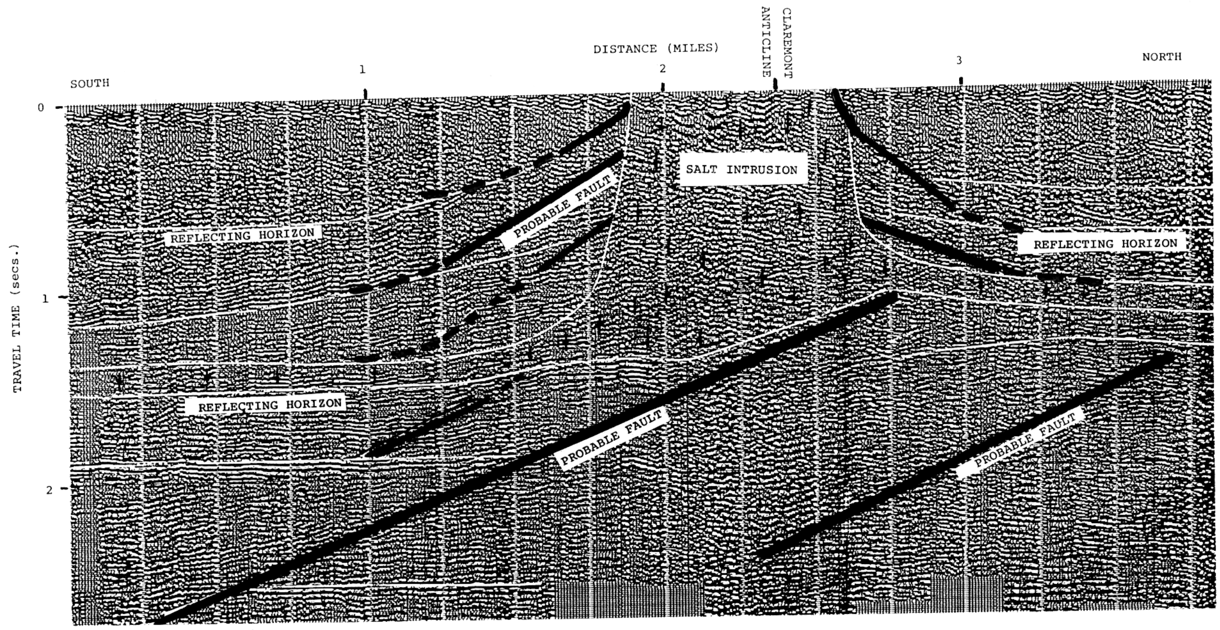
In the Malagash, Hansford, Minudie, Nappan, Wallace River, Beckwith, and Cape John areas there are numerous faults, commonly with less than 500 m displacement. These faults occur in areas of diapiric domes and anticlines and are probably genetically related to extensional stresses caused by evaporite emplacement. The most noteworthy of these faults are the: (1) Golden Brook Fault, (2) Malagash Mine Fault, (3) Hansford Fault, (4) Cape John Fault, (5) Lazy Bay Fault, (6) Beckwith Fault, (7) Fox Harbour Fault, (8) Little River Fault, (9) Black River Fault, (10) Mt. Pleasant Fault, (11) Glenville Fault, and (12) Oxford Fault (Fig. 5-2). These faults commonly comprise a series of closely-spaced faults rather than a well defined single fault trace. Fault orientations show two principal trends: (1) dominantly east-west to east-northeast and (2) a transverse subordinant trend of north-south to northwest.

The faults generally exhibit normal dip-slip and minor strike-slip movement, although larger displacements are suspected but difficult to confirm. The sense of relative strike-slip movement is sinistral but locally appears to be dextral. This is in contrast to the dextral displacement (late Paleozoic) along the North and the Cobequid - Chedabucto Fault System. Although the relative displacement of stratigraphic units by faults appears to be sinistral (perhaps related to sinistral Mesozoic movement), slickensided surfaces in some fault zones indicate normal dip-slip or dextral strike-slip movements predominated. This observation is supported by seismic information across domal structures, where listric normal faulting radiates around the domes (e.g. Malagash; Fig. 5-7). Reidel shear sets are found in proximity to the Cape John Fault. These conjugate fractures indicate extensional stress oriented northwest-southeast. This can probably be attributed to diapirism north of the Cape John Peninsula. This pattern is also reflected in scattered transverse faults which offset the principal east-west structures.

On the basis of structural data compiled from field mapping, seismic interpretations, and geological cross-sections, it is apparent that many of the minor faults of the eastern Cumberland Basin are genetically related to diapirism. Diapirism was probably triggered and controlled by earlier, deep basin faulting. The fault zones, exposed at surface within the basin, may record a complex movement history involving reactivation zones that exhibit different displacements but similar orientations to the earlier basin-forming fault systems (i.e. pre- to syn-Carboniferous versus Permian to Mesozoic).

Pugwash Diapir

Folding in the eastern part of the Cumberland Basin takes the form of gentle synclines which contrast with the intervening, steep axially faulted anticlines. The disrupted anticlines are cored by diapiric evaporites of the Windsor Group as discussed earlier. Internal folding within the diapiric structures has been described by Evans (1972). Carter (1987) produced three-dimensional reconstructions of anhydrite units in the Canadian Salt Company Ltd. Pugwash Salt Mine (Fig. 5-8 to 5-10). He described these as extremely deformed, vertical curtain folds, typical in piercement diapirs. Detailed documentation of folds within the Pugwash salt deposit is currently in progress (Carter, 1990 and in prep.), and these observations should greatly enhance our understanding of diapir emplacement.



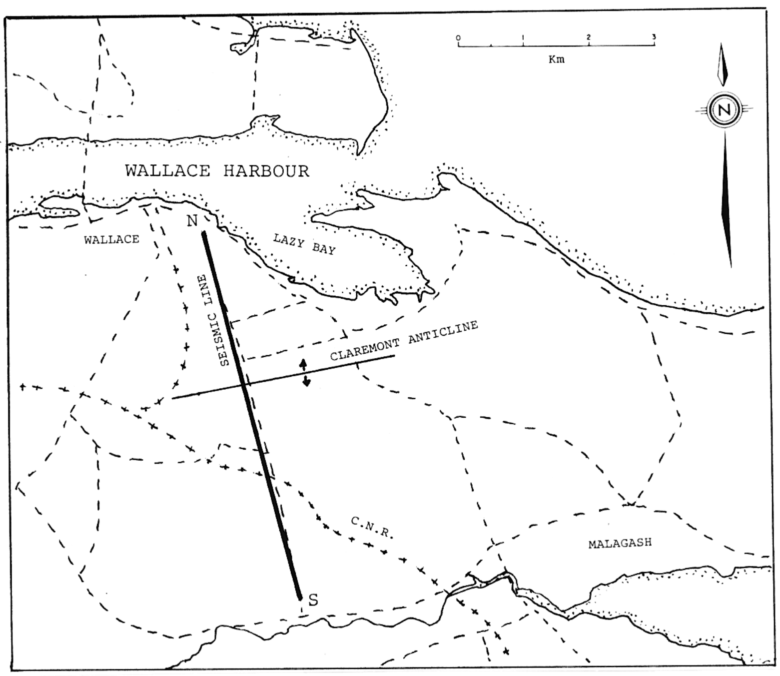


Figure 5-7. Seismic interpretation for a line across the Claremont Anticline near Malagash, Nova Scotia.

The complicated structure was not recognized during initial surface diamond-drill exploration at Pugwash. According to Evans (1972), most folds in the halite units can be classified as similar and quasi-similar folds with steeply dipping axial planes and parallel to subparallel isoclinal limbs. The thin anhydrite interbeds have similar geometry. Refolding of these tight folds has produced complex fold forms characterized by closures, crescent-shaped closures and hooked overfolded forms. Evans (1972) attributed the interfering fold forms to a single, prolonged period of deformation rather than discrete events. Halite responded to stress in a ductile, plastic manner and ('flowage') changed shape extensively, with attenuation so severe as to eliminate parts of the sequence.

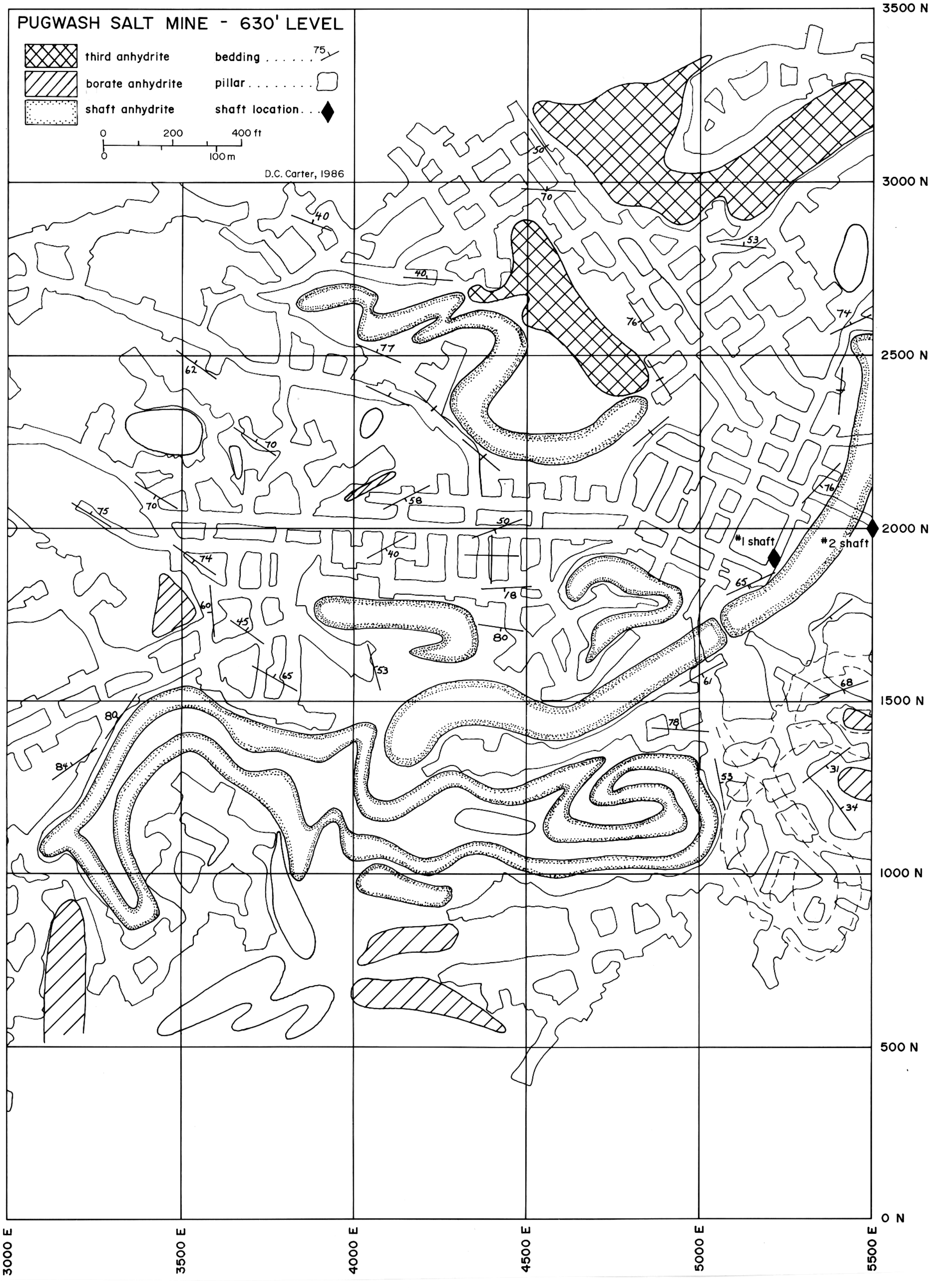


Figure 5-8. Simplified geology, 630 Level in the Pugwash Mine (after Carter, 1990).

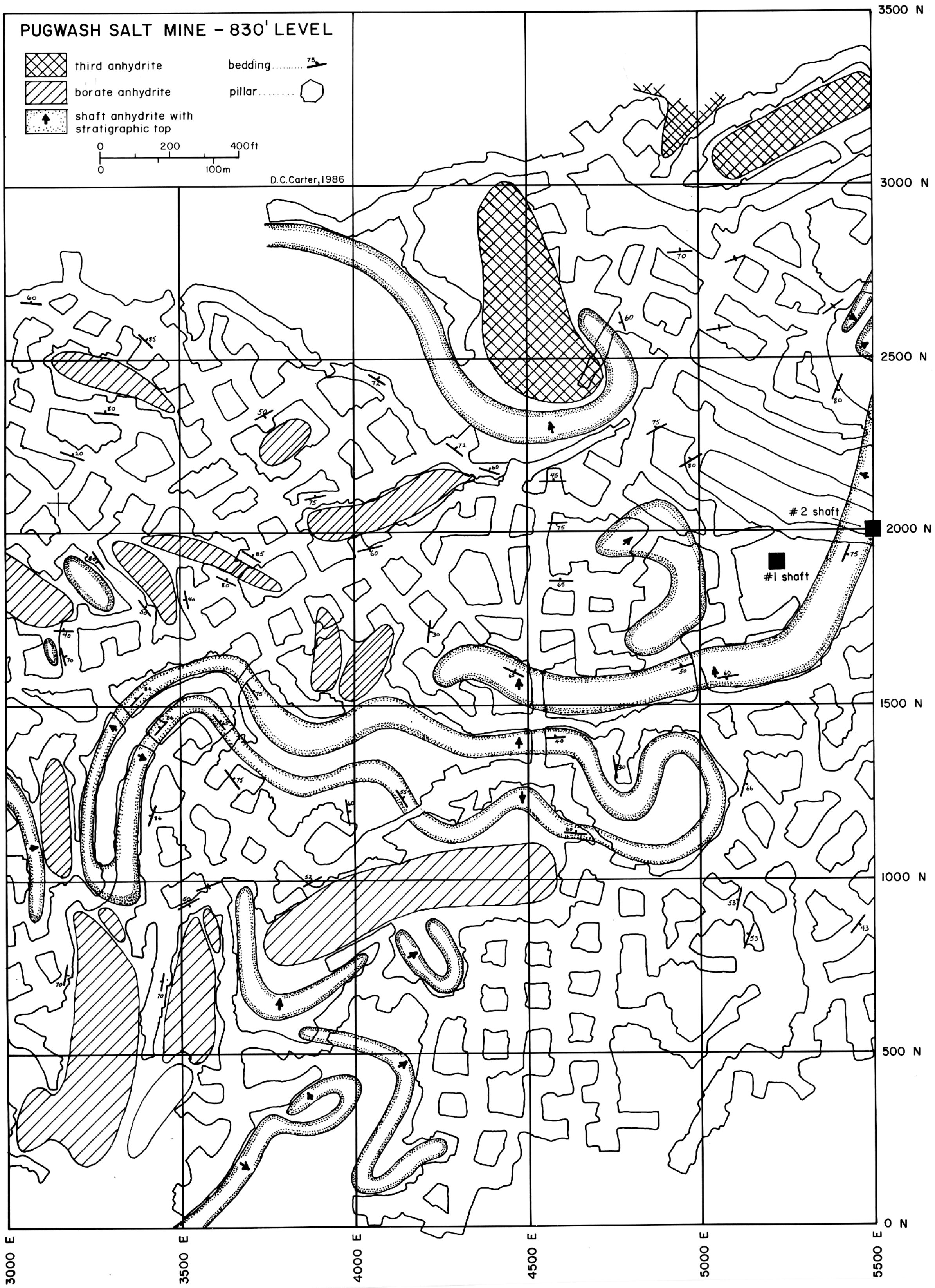


Figure 5-9. Simplified geology, 830 Level in the Pugwash Mine (after Carter, 1990).

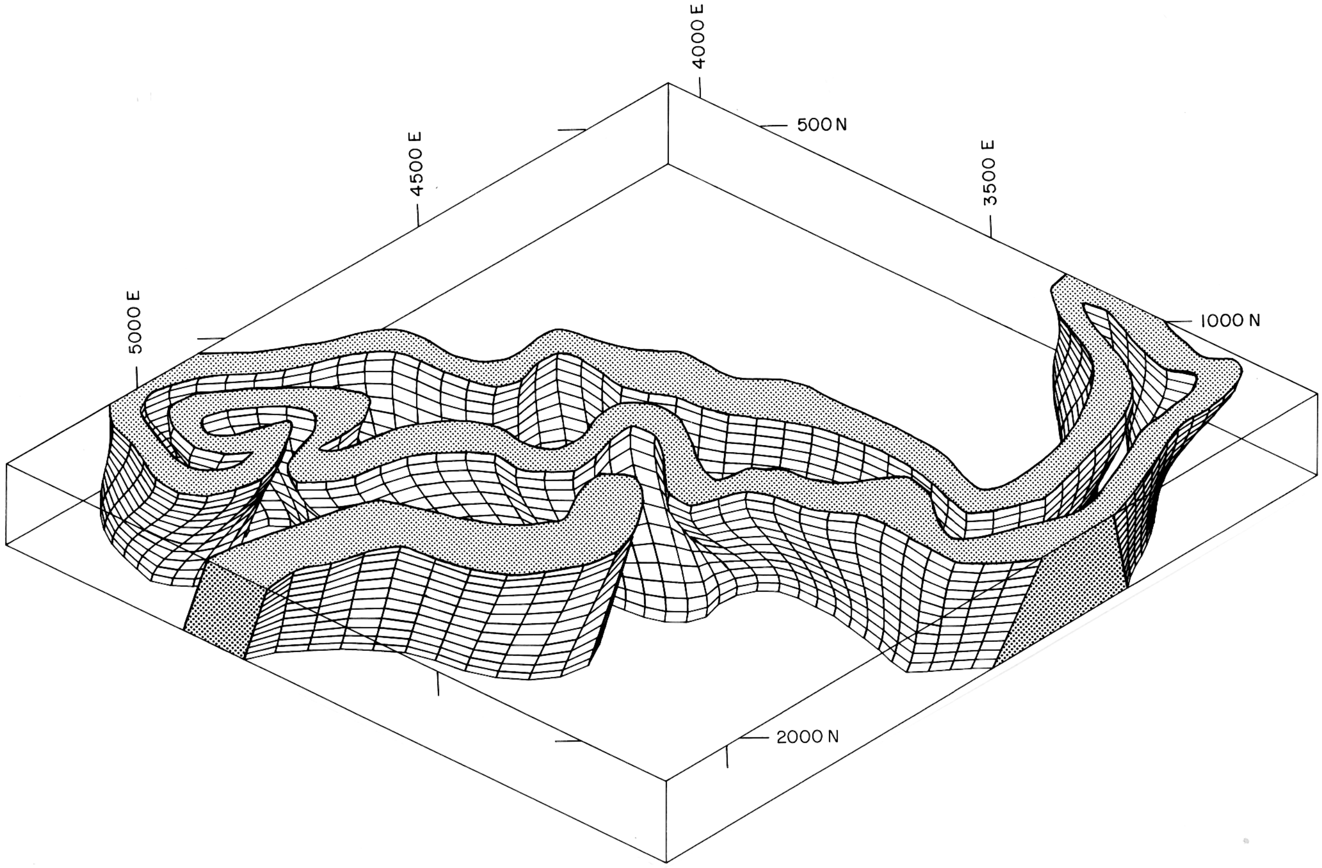


Figure 5-10. Block diagram of the shaft anhydrite unit, Pugwash Mine (Carter, 1990).

Some of the thicker anhydrite units (e.g. the Borate Anhydrite unit, up to 30 m; Carter, 1990), in contrast, were relatively competent and upon folding were broken, dislocated, boudinaged and carried as passive rafts within the flowing salt. The thick Shaft Anhydrite unit, however, displays intermediate folding characteristics with both larger scale boudinage and dislocation as well as complex, moderately tight internal folds, although they not as extreme as those in the salt units.

According to Carter (1987) the structure is dominated by curtain folds with nearly vertical fold axes. Similar sequences were described by Richter-Bernberg (1980) as being typical of a thinning salt deposit due to extrusion of salt at surface (emigration). Carter (1987) concluded that the Pugwash salt deposit represents a true piercement diapir and that the present volume of salt may be a remnant due to emigration-related thinning of the former salt body (Fig. 5-8, 5-9).

Three fold trends were described in the Pugwash diapir by Evans (1972). One trend is parallel to the east-west fold axis in the flanking Late Carboniferous cover. The second trend is perpendicular to the first and both were attributed to the influence of Late Carboniferous folding on the growing diapir. Interfering fold patterns resulting from the complex stress regime were reported from the central area of the structure by Evans (1972). A third trend oriented slightly southeast was recognized on the northwest border of the structure. Fold axes generally displayed a radial arrangement typical of domal diapiric intrusions (Fig. 5-10). Evans (1972) concluded that the fold configuration and the severity of deformation were consistent with diapirs but suggested the Pugwash structure was intermediate between a piercement diapir and a deformed anticline.

Malagash

The internal structure of the Windsor Group diapiric evaporites was also documented to a limited extent in the workings of the abandoned (1919-1959) Malagash Salt Mine. The mine was located near the south-dipping limb of the Claremont (Malgash) Anticline (Fig. 5-7). North of the mine site the anticlinal structure is broken by faults and is apparently asymmetric like the north limb of the

Minudie Anticline. Late Carboniferous Cumberland Group strata are in complex fault (intrusive) contact with Windsor Group evaporites and Mabou (Canso) Group redbeds (Fig. 5-4d). Mine workings closely followed the moderately to steeply dipping salt horizons, which were only 2-5 m thick. The workings extended from approximately 30 m below surface to a vertical depth of approximately 350 m, and defined in detail a complex fold pattern over an east-west strike length of nearly 500 m. The fold pattern has the geometry of an asymmetric S shaped fold (viewed from above) with hanging wall repeated by folding over a strike width of 100-200 m (Fig. 5-11). The south-dipping axial plane is nearly planar, parallel with the strike of the anticlinal axis. The mine fold axis is curved, noncylindical, plunges south and varies from reclined to subhorizontal. A linkage or interpretation of the fold into the larger scale structure is not possible; however, it serves to illustrate an aspect of the structural complexity as well as the ingenuity of the mine operators to produce such a low value commodity for 50 years from such a thin complicated deposit.

Minudie: King Seaman Syncline

Fold structures at the scale of hundreds of metres are rarely as well exposed as they are in the King Seaman Syncline near Minudie. This overturned structure is located on the complex north limb of the Minudie Anticline along the western shoreline of River Hebert. Shepody and Middleborough formation strata of Viséan to Namurian age are continuously exposed for approximately 1 km in low cliffs (3-10 m high) and in the intertidal shore face. The section from south to north is described in the following paragraphs. Beginning at the dilapidated Minudie wharf are east-west striking, steeply dipping (70-90° south) and overturned redbeds of the Middleborough Formation (Fig. 5-12). The degree of overturning increases up to 30° along section to the north for approximately 500 m to the base of a prominent outcrop of grey sandstone where there are dips of 50° overturned south. This section has locally erratic attitudes due to small scale folds and faults.

The grey sandstone body is well exposed and overturned, with 50 to 85° dips to the south. It is faulted and disrupted at the erosive base with abundant copper mineralization in the channel lag. The fining upward trend and sedimentary structures clearly indicate younging to the north. The same sand body, with a north-south strike and gentle (16°) dip to the west, occurs in a right-way-up configuration immediately to the north of and continuous with the overturned section. The right-way-up section of Middleborough Formation redbeds beneath the grey sandstone continues in low cliffs to the north for approximately 400 m and contains abundant ripple drift crossbeds identical to those exposed in the steeply overturned limb to the south. Fold repetition of the grey sandstone channel body is documented in, and can be traced through, a disrupted axial area in the intertidal shoreface. Small scale folds, fault offsets and slickensides are present in the tight fold hinge. The fold axis orientation is difficult to determine accurately but generally trends west-southwest and plunges gently to the west.

The north limb of the King Seaman Syncline continues to be gently dipping and south facing as far as the outcrop limits in the north. It must, therefore, be a subordinate fold and/or a faulted block on the northern limb of the Minudie Anticline where north dips or facing directions would be appropriate. This asymmetry is consistent with the faulted nature of both the Minudie and the Claremont - Malagash anticlines which characteristically have nearly normal south limbs but faulted north limbs. The north limbs generally have complex, overturned fault blocks and high-angle reverse to overthrust geometry. Examples of this type of structure are present in the Minudie Anticline east of Minudie near Lime-kiln Brook, as well as near Fenwick and Brookdale. These areas have complex structures comprising: (1) overturned fault blocks of Boss Point Formation rocks as a wedge or keystone in the axial region of the anticline near the termination of the Nappan Diapir outcrop, and (2) folded fault blocks of Windsor Group to Boss Point Formation rocks near the north side of the faulted anticline. The overturned folding and complex fault blocks on the north side of the Minudie Anticline are consistent with a major overturned fold structure in the Sunoco No. 1A borehole described by Howie (1988). Rocks at the bottom of this borehole were originally correlated with the Horton Group. Based upon palynology, Howie (1988) established them as Canso-Riversdale Group, overfolded beneath overthrust diapiric evaporites of the Windsor Group.

Basin Development Structures

Structures that may be related to basin subsidence, or growth, include: (1) faults within the basin away from the diapiric structures, (2) possible thrust faults, (3) joints and (4) folds. It is difficult in most instances to accurately determine the timing of jointing or minor faulting. Many of these structures probably represent later events, such as Triassic rifting, and therefore do not reflect penecontemporaneous basin subsidence features. Detailed documentation and analysis of these features is beyond the

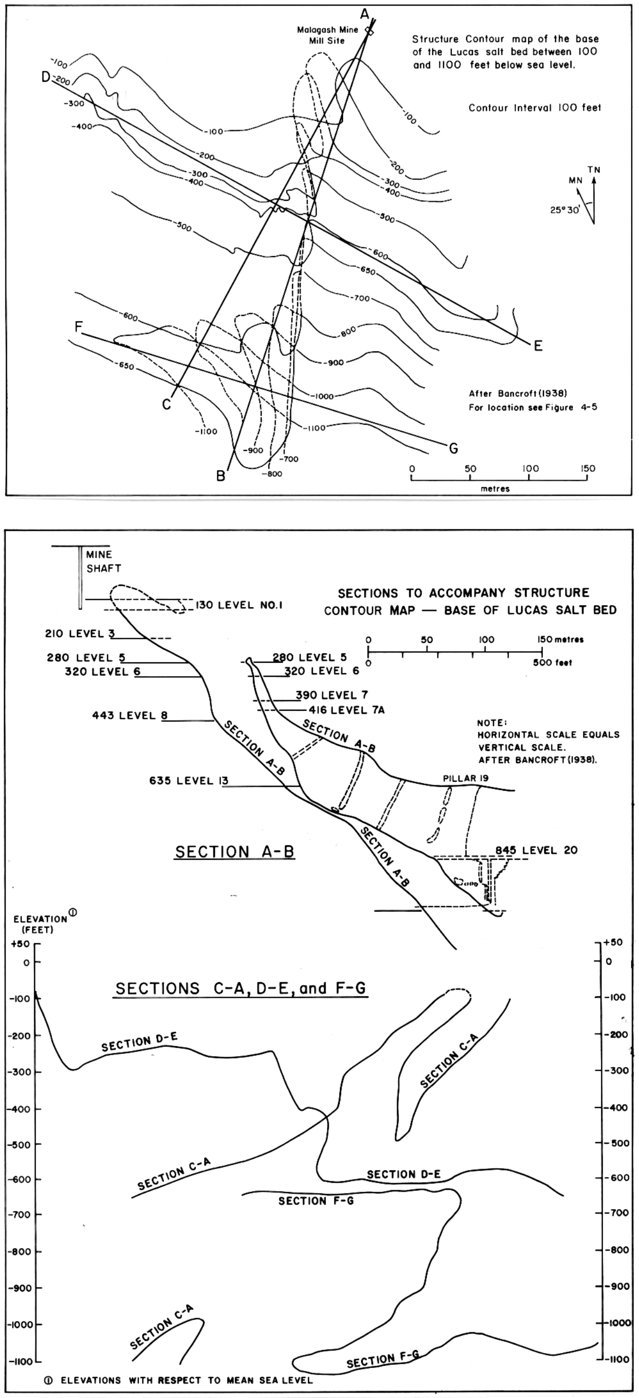


Figure 5-11. Structure contour map on base of the Lucas Salt bed with accompanying sections, Malagash Mine.

scope of this study, and only preliminary observations are presented. Reed (1992) examined the structures of the western Cumberland Basin and concluded that the Athol Syncline and Springhill Anticline, as well as northwest-trending faults resulted from transpression during dextral movement in the early Westphalian. Reed (1992) also suggested that superimposed on these transpressional structures were extensional faults and folds related to Mesozoic sinistral movements on the major faults.

Basin Synclines

The Athol, Tatamagouche, Wallace and Amherst synclines are the most areally extensive structural features in the Cumberland Basin. They are gently plunging to doubly plunging with curvilinear axes and a general east-west orientation (Fig. 5-2). The Athol and Amherst synclines follow an east-northeast trend and perhaps may reflect their proximity to the major structural re-orientation along the northwest border of the basin (Westmoreland Uplift, Sackville Sub-basin and Caledonia Highlands Massif; Fig. 5-2). A seismic line through the Athol Syncline (Fig. 5-13) presented by Calder and Bromley (1988) clearly shows a thickened sequence of strata at the synclinal axis, indicating that the syncline developed syndepositionally. In addition, early Mesozoic to Cenozoic tectonism may also have resulted in minor faulting, folding and deformation in the synclines as well as elsewhere in the basin. The Wallace Syncline, located between the Claremont and Minudie anticlines, is extensively disrupted by faults and evaporite diapirs. The other synclines, in contrast, are relatively unbroken, with the possible exception of the central parts of the Athol Syncline (Athol, Sand River and Sand Cove faults) as well as its termination near Springhill against the end of the Claremont Anticline.

Hastings Uplift

The Hastings Uplift (Howie, 1988) is a buried uplift or fault block situated near the western apex of the Amherst Syncline, immediately north of the Minudie Anticline (Fig. 5-2). The precise configuration of this block is not clearly defined; however, Howie (1988) indicates an east-west extension to the north of the Minudie Anticline. The southern flank is inferred to be present in Gulf *et al.* Hastings No. 1 drillhole which intersected basement rocks at a depth of 2837.7 m. Lower Carboniferous strata were apparently absent or only very thin and a major onlap-overstep relationship was interpreted by Howie (1988). The area between the Minudie Anticline and the Sackville Sub-basin is structurally complex (Martel, 1987).

Jointing and Small Scale Faulting

The orientations of joints and faults with minor displacements in the Cumberland Basin show a polymodal distribution. Three preferred orientations, north-south (015°), east-west (090°), and northwest-southeast (135°),

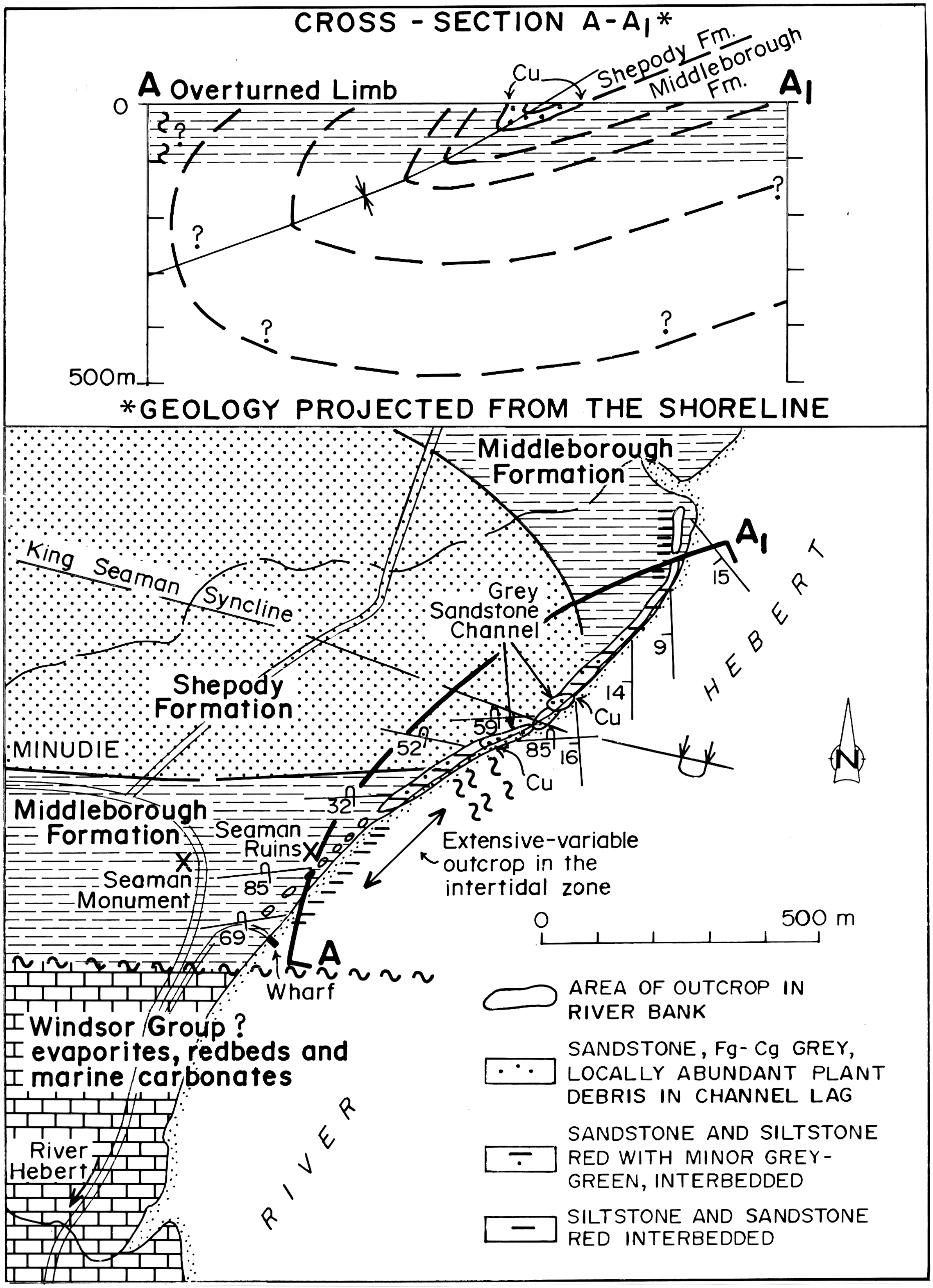


Figure 5-12. Geology and cross-section through the King Seaman Syncline near Minudie.

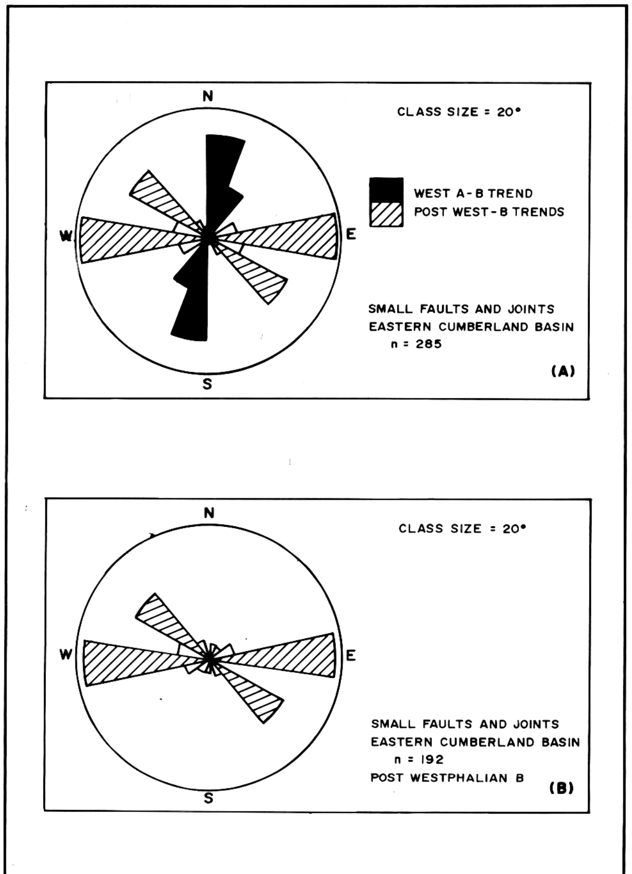


Figure 5-13. Rose diagrams of fault and joint strikes in the Cumberland Basin.

were observed (Fig. 5-14). Seasat imagery for northern Nova Scotia (Fig. 5-15) shows lineaments that correspond very well to field observations (Fig. 5-14). The dataset from field observations can be divided into two subsets on the basis of the age of deformed rocks: (1) pre-Westphalian B strata and (2) post-Westphalian B strata. The two subsets are distinctive, with the older subset having east-west, north-south and northwest-southeast preferred orientations, whereas the younger strata only exhibit east-west and northwest-southeast joint and fault orientations (Fig. 5-14). This may indicate that the north-south structures originated before the Pre-Westphalian B and, consequently, they are contemporaneous with basin subsidence. Timing of the joints and faults with other orientations remains unclear, but perhaps they are related to Permian to Mesozoic tectonics.

Cumberland Basin Development

The following section is an attempt to synthesize the sedimentology, stratigraphy, and structural geology of the Cumberland Basin with the goal of deriving a compatible tectonic and basin development model. The Cumberland Basin model(s) will then be briefly considered in relation to the current models of the Maritimes Basin.

The Cumberland Basin is the structural remains of a relatively deep (7000 m+) sedimentary basin which developed just north of, and apparently parallel with, the east-west strike-slip zone of the Cobequid - Chedabucto Fault System. This complex, tectonically disrupted zone marks the suture between the Avalon Composite Terrane and the Meguma Terrane.

The western margin of the Cumberland Basin is a structurally complex area where it converges with the dominant, regional northeast structural trend in southeast New Brunswick. South of the juncture of the Caledonia Highlands Massif and the Harvey - Hopewell Fault there is a significant reorientation of the structural features in the basin, from east-west to northeast-southwest (Gussow, 1953; Ruitenberg and McCutcheon, 1982; Nance and Warner, 1986). This adjustment in trend coincides with a change from the strike-slip movements of the eastern basin to the mid-Westphalian thrusting and high-angle reverse faulting in southern New Brunswick (Gussow, 1953; Nance and Warner, 1986).

Stratigraphic sections for various areas adjacent to the Cobequid Highlands Massif have been compiled as part of this study (Fig. 5-16). These sections were used to evaluate onlap relationships and sedimentary facies adjacent to the highlands. These data were supplemented by the sedimentological data, particularly sediment dispersal trends and facies variations, in order to create, by backstripping, a series of paleogeographic reconstructions for various times in the basin's development (Fig. 5-17). Ryan *et al.* (1987) suggested that the Carboniferous strata may be considered to comprise three packages. These reflect major tectonic events and perhaps related or coincident paleoclimatic changes that have affected the basin fill history. The three sedimentary megasequences are: (1) Upper Devonian to Namurian, Fountain Lake Group to the Mabou (Canso) Group; (2) upper Namurian to mid-Westphalian A, lower part of the Cumberland Group (formerly included in the Riversdale Group); and (3) late Westphalian A to Lower Permian, upper part of the Cumberland Group and Pictou Group (Ryan *et al.*, 1987; Fig. 5-18).

Each megasequence records a deceleration of the subsidence rate. Initial rapid subsidence (and/or uplift) resulted in local deposition of fanglomerates at the basin margins (cf. Fralick and Schenk, 1981). These marginal coarse deposits were succeeded by a transition to fluvial,

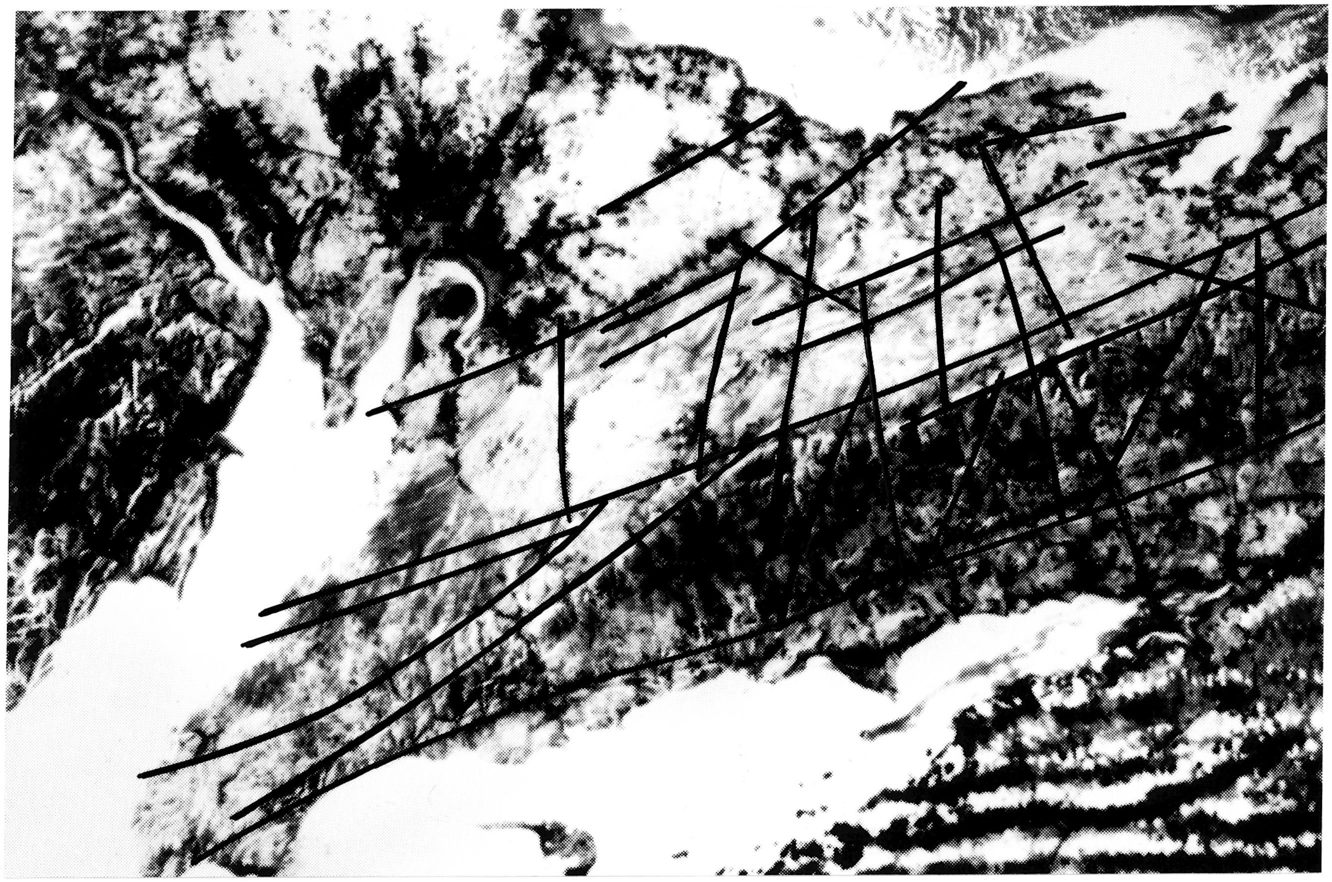


Figure 5-14. SeaSat image with linears from northwestern Nova Scotia.

lacustrine, and in one case, marine basin-fill. Fluvial-lacustrine deposition was more widespread. The later episodes of basin infilling overlap older basin strata in some areas, possibly reflecting a slower subsidence rate. Each of these sedimentary megasequences probably records a tectono-sedimentary allocycle. The timing of these events corresponds to similar cycles in the Stellarton Graben (Yeo and Ruixing, 1987), suggesting that these were regional in extent.

These allocyclic packages are useful simplifications of the large-scale depositional trends and aid in understanding the relationships between local and regional tectonic activity (Ryan *et al.*, 1987).

Late Devonian - Early Namurian

Fountain Lake Group and Horton Group strata probably exceed 4000 m in thickness. They record the earliest sedimentation during initial basin development following the deformational phase of the Middle Devonian Acadian Orogeny. Continental deposition occurred in intermontane rift basins with represent alluvial fan, fluvial and lacustrine environments (Donohoe and Wallace, 1985; Carter and Pickerill, 1985a, 1985b) predominating in these intermontane basins. Locally these strata are interbedded with basalt and rhyolite. The large volumes of detritus derived from local highlands resulted in rapid sedimentation and facies variation. Alluvial fanglomerate facies thin basinward and up-section into laterally equivalent fluvial to lacustrine facies (Ryan *et al.*, 1987). The relationships of these facies during the Late Devonian to early Namurian are not well documented, and are poorly exposed because they have been overstepped by younger strata.

Horton Group sedimentation ended when a marine invasion occurred during the Viséan (Boehner *et al.*, 1986). An arid climate and restricted inflow resulted in the deposition (up to 1000 m) of a multi-cycled sequence of saline marine evaporites, fine to coarse redbeds, and thin but laterally extensive marine carbonates of the Windsor Group (Giles, 1981). Lower Windsor Group deposition was consistent and laterally widespread throughout the Maritimes Basin (Moore and Ryan, 1976).

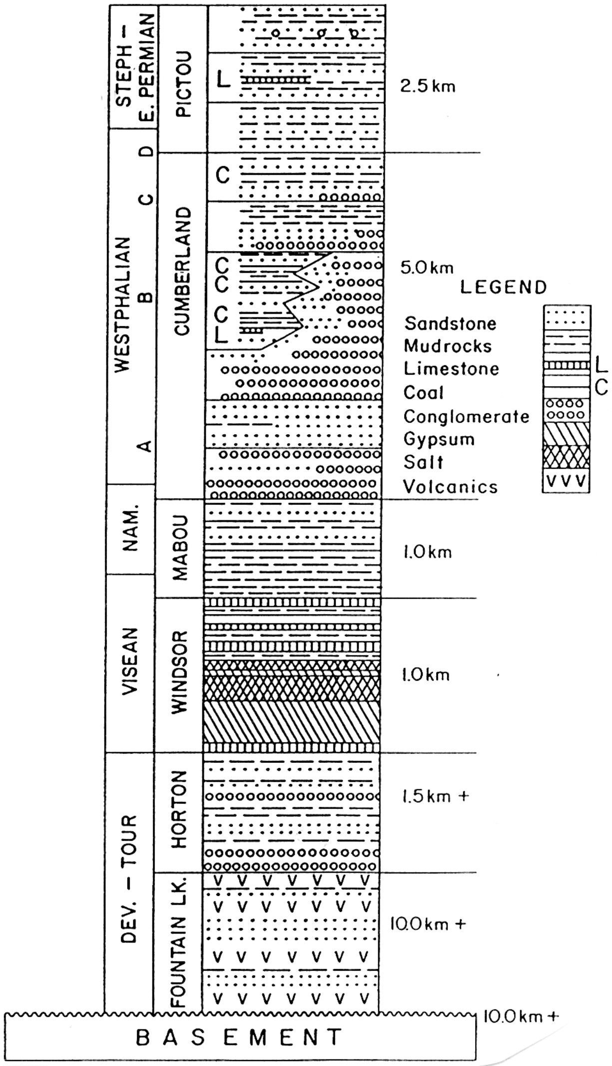


Figure 5-15. Generalized stratigraphy of the Maritimes Basin.

The restricted marine, evaporitic sedimentation of the Windsor Group was succeeded by up to 1500 m of continental deposits of the Mabou (Canso) Group. These fine-grained, red to grey fluvial-lacustrine facies (Belt, 1965; Bell, 1944) were deposited throughout much of the Cumberland Basin and Maritimes Basin from the late Viséan to early Namurian.

The Upper Devonian to lower Namurian package, therefore, records: (1) rapid initial basin subsidence, continental alluvial, fluvial-lacustrine deposition with associated early volcanism, succeeded by (2) mixed marine carbonates and evaporites with redbeds and (3) subsequently succeeded by fluvial-lacustrine clastics, deposited during a period of slower regional subsidence (Ryan *et al.*, 1987).

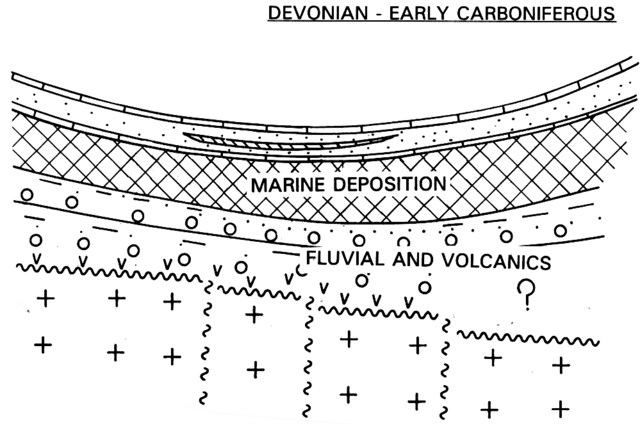


Figure 5-16. Diagrammatic geology of Devonian to Namurian sedimentation represented by the Fountain Lake, Horton, Windsor and Mabou groups in the Cumberland Basin.

Late Namurian - Westphalian A

The lower part of the Cumberland Group diachronously overlies the Mabou Group and contains thick, widespread extraformational conglomerates of the Claremont Formation. These conglomerates are succeeded by more than 1000 m of grey sandstone and fine-grained redbeds of the Boss Point Formation. Boss Point Formation strata represent widespread deposition of sandstone over a large portion of the Cumberland Basin (Fig. 5-17).

In areas near the Cobequid Highlands Massif the Boss Point Formation oversteps older Carboniferous strata and onlaps basement rocks. Boehner *et al.* (1986) confirmed van de Poll's (1966) suggestion that the mature nature of the Boss Point Formation sandstone reflected the initiation of a distal source for detritus.

The Claremont Formation (= Millsville conglomerate, Enrage Formation) fanglomerates were deposited adjacent to the highlands massifs in response to uplift and rapid subsidence. Fanglomerate deposition was followed by a period of slower, more regional subsidence, represented by the sandstone and mudrocks of the Boss Point Formation.

Late Westphalian A - Lower Permian

The Boss Point Formation is conformably to disconformably overlain by younger units of the Cumberland Group. The upper parts (Westphalian B-C) of the Cumberland Group are restricted in distribution and

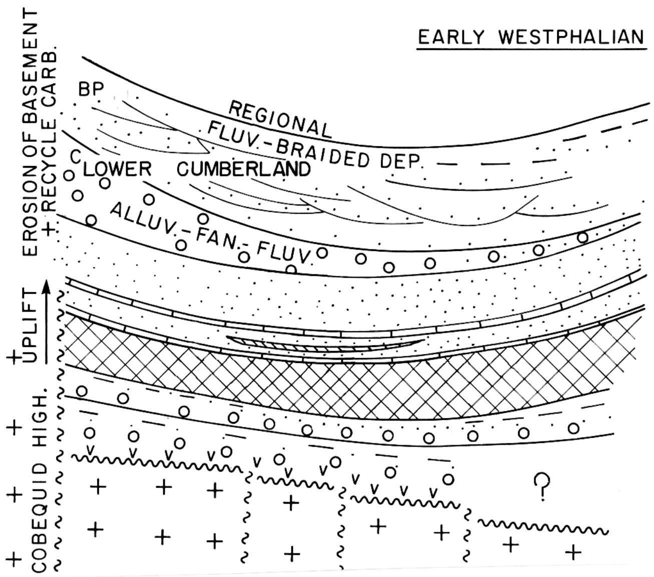


Figure 5-17. Diagrammatic geology of Devonian to early Westphalian sedimentation including the lower part of the Cumberland Group in the Cumberland Basin.

are best developed in the deeply downwarped areas at the western end of the Cumberland Basin (Copeland, 1959) and the Stellarton Basin (Yeo, 1986). Elsewhere in the Maritimes Basin, strata of Westphalian B age are very thin or absent (Ryan *et al.*, 1987).

At least three major episodes of marginal alluvial fan deposition are recorded in the Cumberland Group strata. These conglomerates reflect uplift of the massifs, and coincident subsidence of the basin with development of extensive drainage systems out of the highlands (Fig. 5-17). A range of fluvial channel configurations, including braided (Calder and Naylor, 1985; Salas and Rust, 1986), internally braided to meandering (Calder, 1985b), meandering (Ryan, 1985), anastomosing (Rust *et al.*, 1984), and composite (Ryan, 1985), evolved contemporaneously within the basin. Lacustrine deposits constitute only a minor component of the basin-fill.

Dextral transpression and related thrusting, which occurred during the Westphalian B in the northwestern part of the basin (Nance and Warner, 1986), must have also affected the evolution of fluvial systems (Calder, 1984b; Rust *et al.*, 1984). The second part of this allocycle is represented by the predominantly fluvial redbeds of the Pictou Group (up to 2500 m thick), which exhibit regional overlap onto the adjacent platforms. Pictou Group strata rest disconformably, or with angular unconformity, on older Carboniferous strata and pre-Carboniferous basement rocks. Within the Pictou Group,

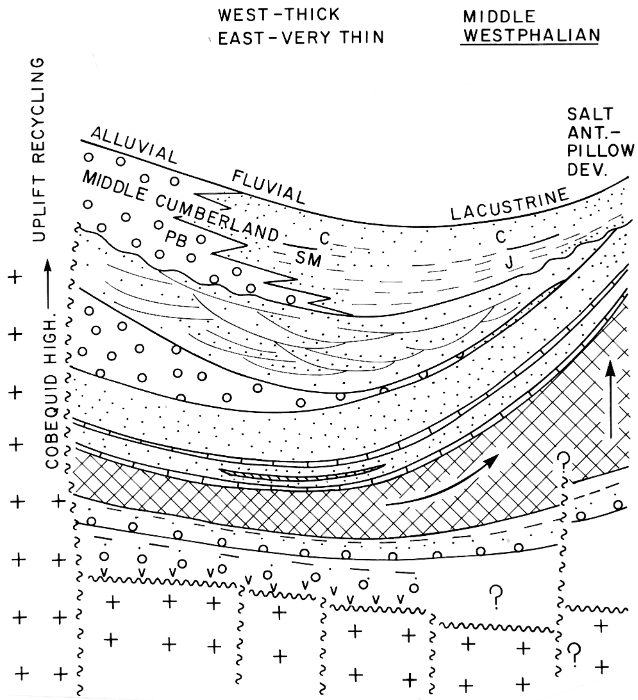


Figure 5-18. Diagrammatic geology of Devonian to middle Westphalian sedimentation including the Polly Brook, Joggins and Springhill Mines formations in the Cumberland Basin.

the decelerating subsidence rate may have resulted in the overall fining upward trend in basin-fill material (Ryan, 1985). Many of the basement and diapir-related faults in the Cumberland Basin are sealed by Pictou Group rocks. Although this indicates their greatest movement was prior to the Westphalian D, faulting and deformation of the Pictou Group occurred in the Stephanian (or later) with local evaporite intrusion (e.g. in the Gulf of St. Lawrence).

Maritimes Basin Development

Maritimes Basin Tectono-Sedimentary History

Late Paleozoic to Mesozoic rocks in Atlantic Canada record a complex history of sedimentation, tectonics and volcanism in the northeast Appalachians. Strata contained within these successor basins reach a maximum thickness of 12 km (Howie, 1988) in the central Gulf of St. Lawrence (Magdalen Basin). They are a complex molassic succession dominated by continental deposition. Sediments were derived both locally (especially in the Late Devonian and Early Carboniferous) and regionally (Late Carboniferous) from the Appalachian Orogen.

These transient depocenters represent the waning stages of the Devonian Acadian Orogeny and subsequent uplift of the orogen following the mid-Devonian docking of the Avalon Composite Terrane and the Meguma Terrane (Fralick and Schenk, 1981). The early Mesozoic records the initial rifting phase of the Proto-Atlantic Ocean and the late Mesozoic to Cenozoic records its subsequent opening.

Late Devonian - Viséan

Late Devonian to early Viséan in the Maritimes Basin was characterized by crustal instability with initial molassic deposition of coarse- to fine-grained rocks of alluvial, fluvial and lacustrine origin associated locally with rift-related volcanic rocks (Fountain Lake Group and Horton Group; Fig. 5-19). Deposition occurred initially under dry seasonal conditions (Late Devonian) then humid lateritic conditions. Extensive lacustrine deposition took place in the early Tournaisian, and evolved through semi-arid dry conditions with local evaporitic lacustrine deposition and redbeds in the late Tournaisian to early Viséan (Howie, 1988; Fig. 5-20).

The basin complex was breached in the early Viséan by a major evaporitic marine incursion of the sub-sealevel landscape (Kirkham, 1978). The Windsor Group evaporitic basin system continued to fill and expand with relatively little coincident tectonic activity. The middle to late Viséan was a time of regionally extensive, restricted marine to evaporitic marine and continental redbed deposition. Numerous minor and major cycles were accumulated in shallow shelf to interconnected intermontane basins. Deposition occurred under hot, semi-arid to arid, stressed environmental conditions.

Namurian - Permian

In the late Viséan to Namurian, continental sedimentation returned and the basins evolved into a broad, low relief floodplain - lacustrine depocenter (Belt, 1968a) dominated by fine-grained sedimentation of the Mabou (Canso) Group, with local fanglomerates in tectonically active areas. This was succeeded by coarse fluvial braidplain deposition with local alluvial fans in the Westphalian A (lower part of the Cumberland Group; Fig. 5-21). The Late Devonian to Namurian stage of basin development has been variously interpreted as rifting to pull-apart tectonics related to major regional and subsidiary wrench faults. Sedimentation patterns within the basin-horst terrane generally reflect local provenance from internal and adjacent basement highland areas, with subordinate (but increasing with time) extrabasinal input. Many basin

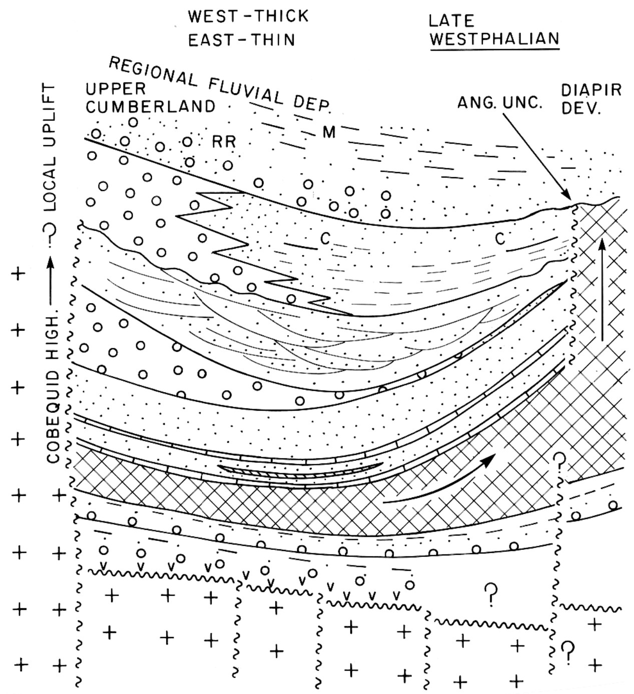


Figure 5-19. Diagrammatic geology of Devonian to late Westphalian sedimentation including the upper part of the Cumberland Group in the Cumberland Basin.

margins are onlap unconformities and thus the basins cannot be interpreted simply as being entirely fault bound.

The arid Viséan climate evolved into a more moderate, pluvial to seasonal climatic regime in the Namurian to early Westphalian. Fine-grained lacustrine to fluvial deposition dominated the Namurian while coarser-grained fluvial braidplain and locally alluvial fan deposition prevailed in the earliest Westphalian, heralding a major change in sedimentary style in the basins. Coarse alluvial fan deposition occurred in the Namurian and is particularly evident in areas adjacent to basement uplifts (i.e. Cobequid and Caledonia highland massifs). Alluvial fans developed in response to movement on the Cobequid - Chedabucto Fault System and related structures. The Westphalian is generally dominated by regional scale fluvial, braidplain and alluvial floodplain deposition.

Extensive shallow (rarely deep), lacustrine to brackish marginal marine and wetland deposition produced the area's major economic coal resources, especially in the late Westphalian (Cumberland Group). The Late Carboniferous to Early Permian records the

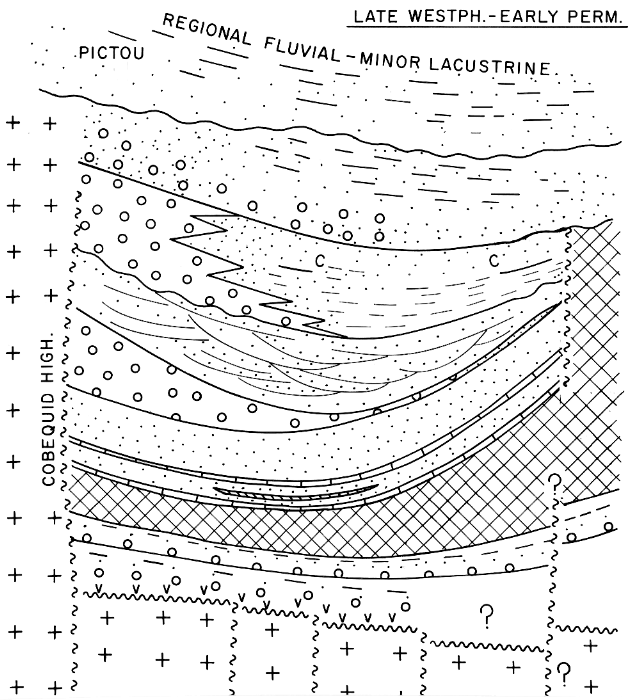


Figure 5-20. Diagrammatic geology of Devonian to Stephanian-Early Permian sedimentation of the Pictou Group in the Cumberland Basin.

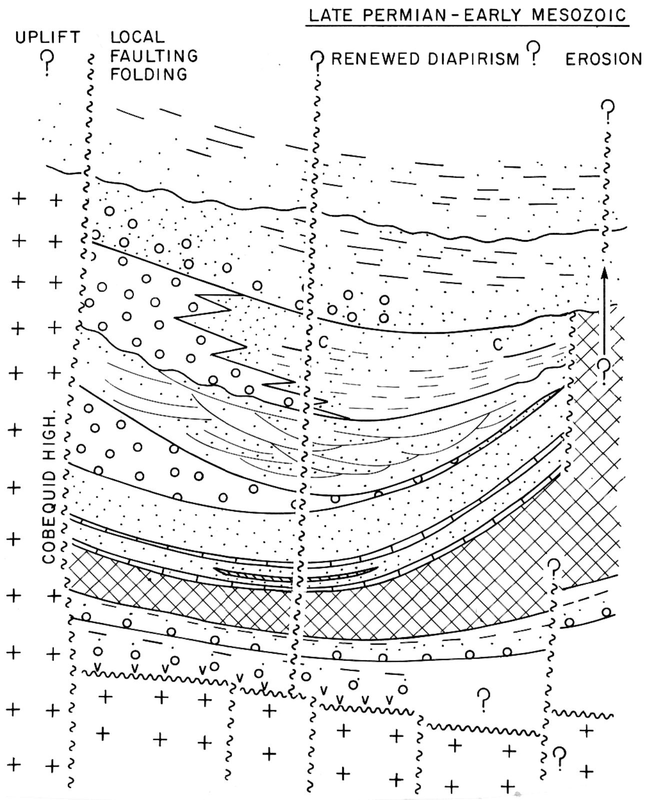


Figure 5-21. Diagrammatic geology of the Pictou Group in the Cumberland Basin including late Permian to early Mesozoic tectonism.

evolution to a drier climate with extensive redbeds and locally reported eolian deposits in the Permian. These conditions are generally similar to the pre-Zechstein evaporite basin conditions in northern Europe and Great Britain. There is no rock record of the Late Permian to Early Triassic in Nova Scotia or in the Maritimes Basin. The Late Permian apparently was a major depositional hiatus and was accompanied by an important reddening episode in Upper Carboniferous strata, especially in the Cumberland Basin.

Major lateral (dextral transform) motion along the Cobequid - Chedabucto Fault System culminated in the mid-Westphalian with complex and locally intense deformation with thrusting, especially in southern New Brunswick (Nance, 1987) as well as other areas adjacent to the fault zone (Fig. 5-22). The deformation locally produced rapid uplift and subsidence with accompanying thick alluvial fan to lacustrine deposition in extensional (local pull-apart) areas. Broad areas of uplift and unconformity, especially in the relatively stable platform areas, accompanied this event (Fig. 5-23). Late Carboniferous to Early Permian generally records regional subsidence and deposition on a large alluvial floodplain setting which fines upward and ultimately is dominated by redbeds (Fig. 5-24). This phase has been characterized as foreland basin deposition (Keppie, 1982b) and was accompanied by coal basin development and overlap of former basement highland and platform areas. Sedimentation was dominated by regional extra-basinal provenance and large fluvial systems with sediment dispersal patterns parallel to the regional basin and basement structural trends (easterly to northeasterly) (Calder *et al.* 1988; van de Poll, 1973; Gibling *et al.*, 1991).

Westphalian Tectonism

The middle to late Westphalian tectonic episode in the Maritimes Basin produced variably intense folding, faulting, uplift and evaporite tectonism, as well as unconformities and recycling of older basin fill. It was an extended episode that peaked in intensity in the Westphalian B and waned through the late Westphalian to early Permian. It has been referred to as the Maritimes Disturbance and related to the Hercynian, Variscan and Alleghenian orogenic events in Europe, the United

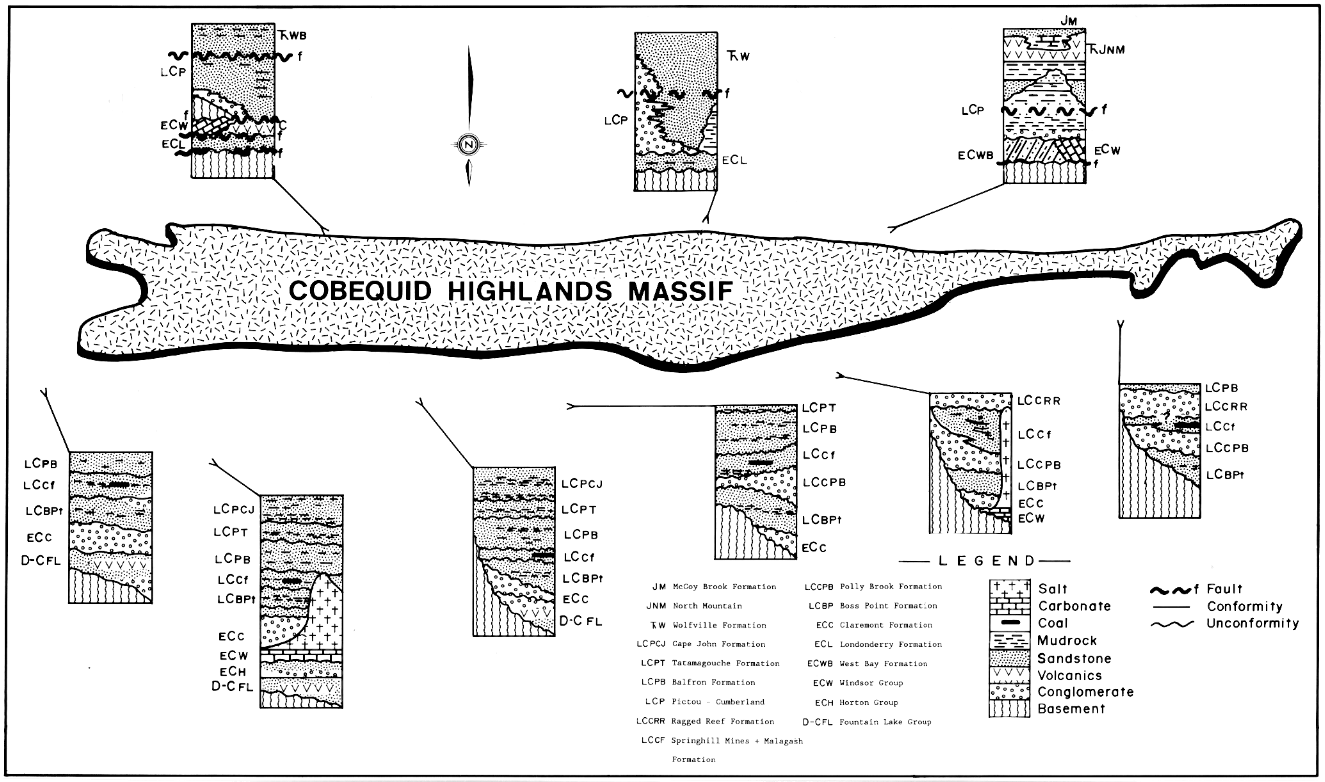


Figure 5-22. Representative stratigraphic sections of Carboniferous basin fill adjacent to the Cobequid Highlands Massif illustrating the complex tectonic and sedimentation history through the Late Devonian to Stephanian-early Permian.

Kingdom and the United States.

The late Westphalian event involved fault and fold deformation related to dextral motion on the Cobequid - Chedabucto Fault System and its subsidiaries. It coincided with locally rapid uplift and subsidence, thick sediment accumulation, especially in the Cumberland Basin and in the central part of the Maritimes Basin in the Gulf of St. Lawrence. Elevated geothermal gradients probably accompanied the deep-seated tectonism, especially in the deeper, rapidly subsiding basins and near the Cobequid - Chedabucto Fault System.

Syn- and post-depositional fault movements in the late Paleozoic to Mesozoic (possibly even Cenozoic) have disrupted and dislocated the original depositional basins, so that many are now structural grabens or half-graben basin remnants (Fig. 5-25). Erosional remains of the late Paleozoic deposition are collectively referred to, in a nongenetic sense, as the Maritimes Basin.

Mesozoic - Cenozoic

During the late Triassic to early Jurassic continental rift sedimentation occurred in the area of the Cobequid - Chedabucto Fault System. Alluvial, fluvial and lacustrine redbeds and tholeiitic basalt were deposited and preserved in narrow graben to half-graben basins in the Bay of Fundy (Fundy Rift), which is located to the south and southwest of the Cumberland Basin, as well as in Chedabucto Bay (Orpheus Graben). A rock record representing this is not preserved or recognized in the Cumberland Basin (Fig. 5-25). Fault and fracture systems affecting portions of the basin fill may, however, be related to Mesozoic tectonics. The Mesozoic basins represent early stage rifting related to sinistral motion on the Cobequid - Chedabucto Fault System during development of the Proto-Atlantic and rest with profound unconformity on the eroded late Paleozoic landscape. Distribution of pre-Cretaceous material beyond the rift areas is unknown but may have been extensive and potentially covered most of Nova Scotia (including parts of the Cumberland Basin) except for the highest highlands.

The only preserved late Mesozoic sedimentation onshore is recorded by unconsolidated interstratified silica sand, kaolinitic clay, and mud with minor lignite coal of early Cretaceous age. These deposits rest on a deeply eroded, late Paleozoic unconformity, especially in central

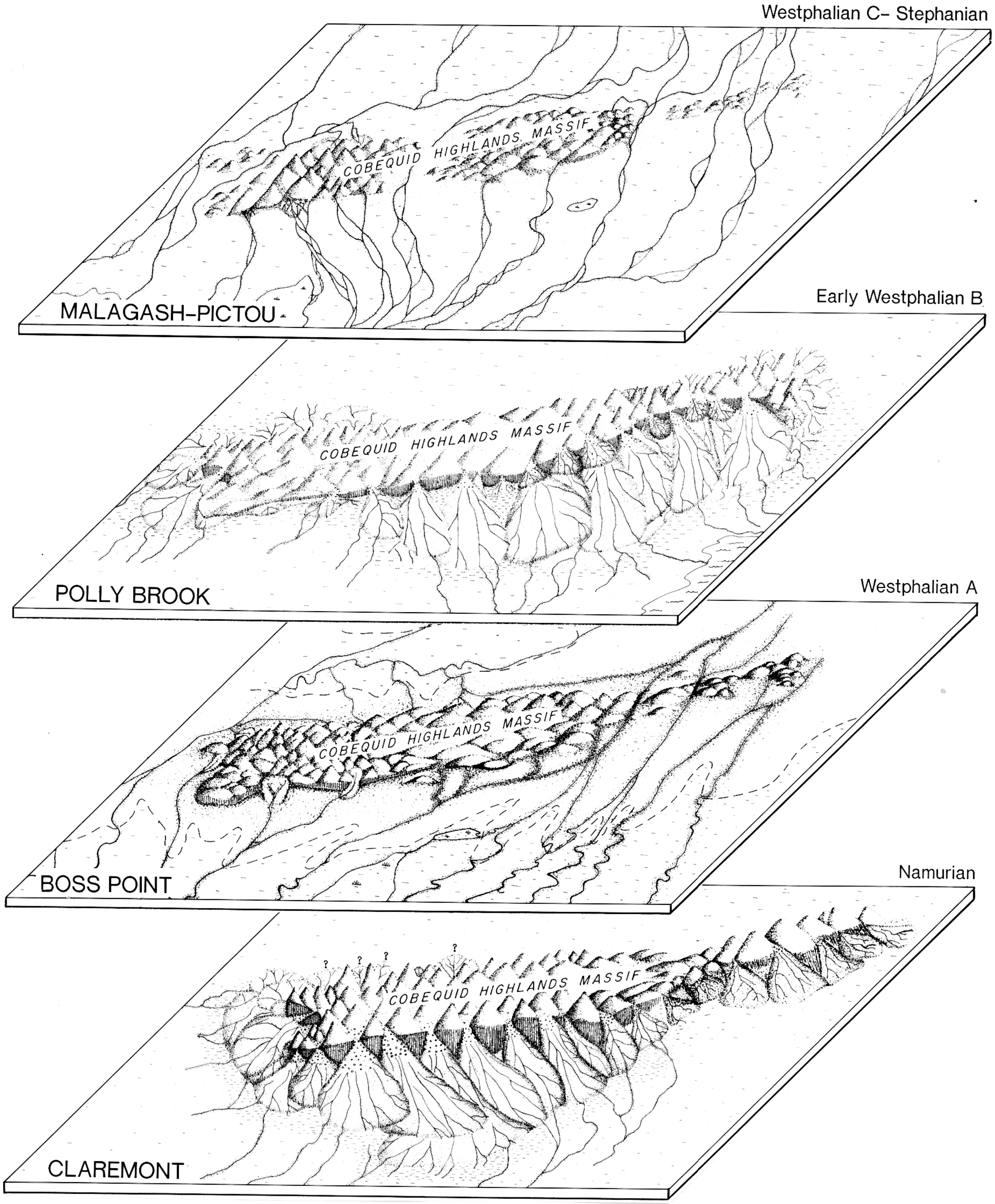


Figure 5-23. Evolution of sedimentation in the area of the Cobequid Highlands Massif through the Late Carboniferous (Namurian) to Stephanian-early Permian.

mainland Nova Scotia. The preserved distribution is probably minor in comparison to the pre-erosional extent. Brightly coloured, grey to variegated mud is locally associated with Windsor Group karsted outcrop areas including Minudie, Oxford and Lazy Bay - Malagash. This material is of unknown age but may be Cretaceous.

The Mesozoic sediments probably represent

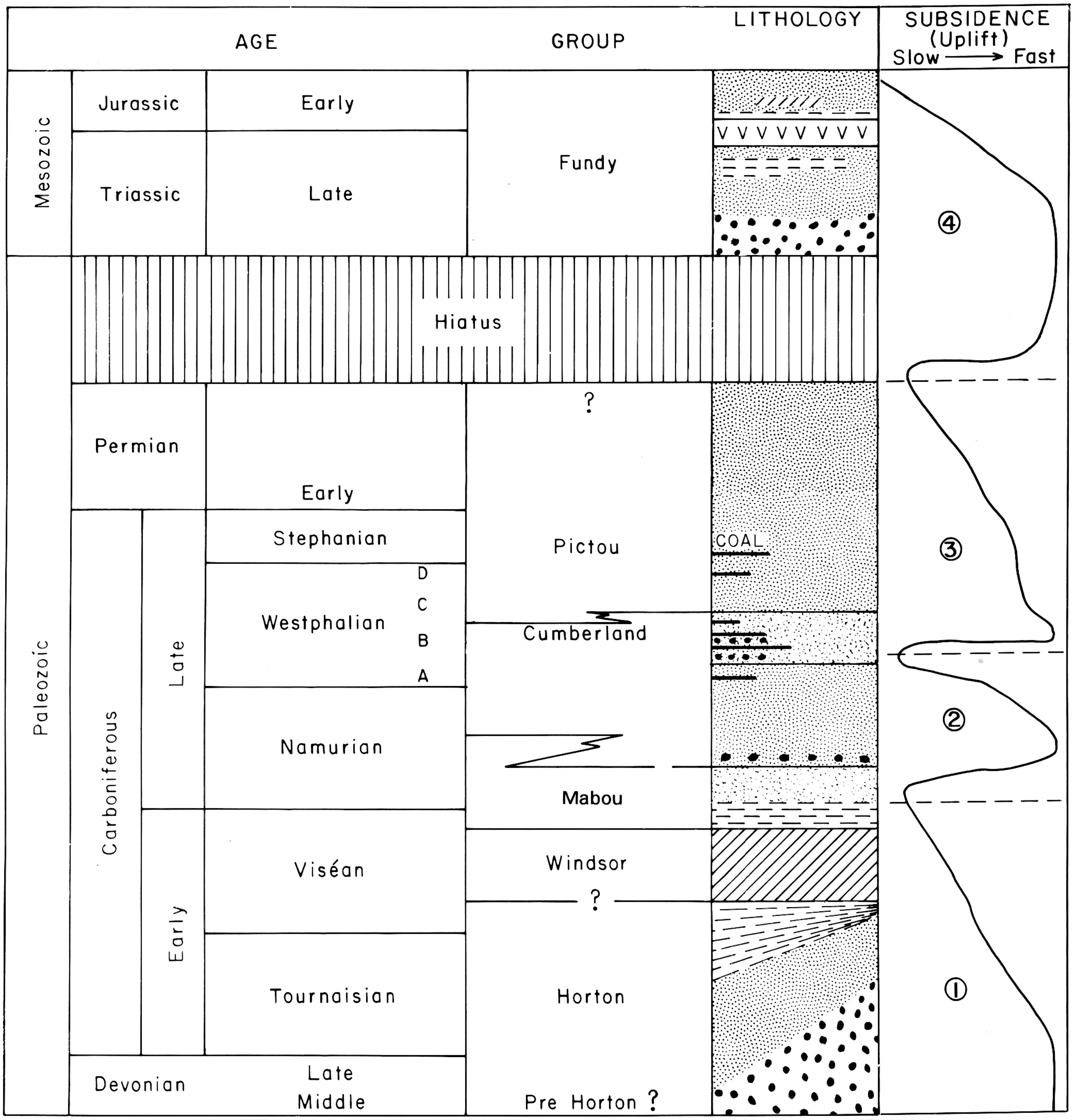


Figure 5-24. Late Paleozoic to early Mesozoic stratigraphy with interpreted subsidence history and megasequences in the Cumberland Basin area.

terrestrial, fluvial to alluvial plain to coastal plain equivalents of the extensive prograding deltaic-marine facies in the Scotian Basin. They generally record deposition as an accretionary prism along the subsiding shelf and continental margin of the opening Atlantic Ocean. No preserved sedimentary record occurs onshore for the late Cretaceous to Tertiary.

Tectono-Stratigraphic Models

Numerous conflicting interpretations have been proposed for the tectonic history of late Paleozoic basins in the

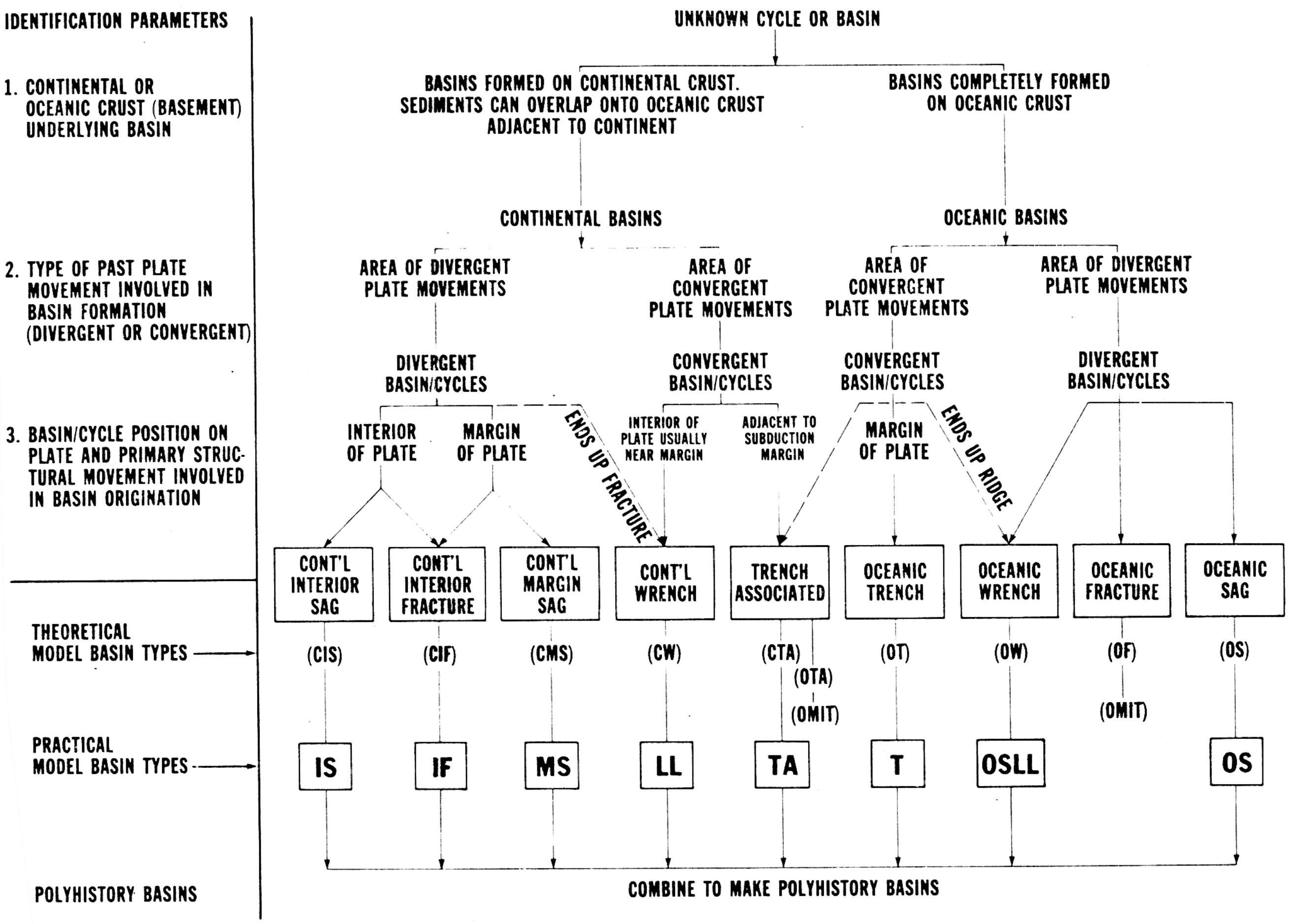


Figure 5-25. Basin classification scheme, after Kingston *et al.*, 1983

northern Appalachians of Atlantic Canada (e.g. Bell, 1944; Gussow, 1953; Belt, 1968a; Webb, 1969; Poole, 1976; Keppie, 1977, 1982a, 1982b; Williams, 1974; Fralick and Schenk, 1981; Bradley, 1982; McCutcheon and Robinson, 1987. Bell (1944, 1958) and Gussow (1953) emphasized the composite nature of the Carboniferous "basins" and described them as intermontane troughs or miniature geosynclines. Normal faulting was thought to have taken place at or near the basin margins.

Subsequent workers (Belt, 1965; Webb, 1969; Fralick and Schenk, 1981; Bradley, 1982) emphasized the importance of strike-slip movement along the basin margin faults. Despite the conflicting views on the history of faulting, uplift and subsidence, most interpretations state or imply a two-part character to the history of sedimentation and tectonism (Boehner *et al.*, 1986; Ryan *et al.*, 1987). The first stage involved an Late Devonian to mid-Westphalian continental and marine deposition within elongate basins bordered by highland areas. The second stage was characterized by widespread fluvial deposition during the late Westphalian to Early Permian. Younger strata widely overstepped earlier basin margins and onlapped the basement rocks of adjacent platforms and uplands, as well as internal highland massifs.

Bradley (1982) proposed a two-phase deposition of Carboniferous strata caused by initial rifting in a dextral strike-slip tectonic framework or "pull-apart basin", followed by a phase of regional thermal subsidence. Keppie (1982b) applied the term transpression in reference to the early pull-apart phase described by Bradley (1982) and suggested that the second phase involved deposition in a "foreland basin" setting. This two-phase subdivision, although generally applicable, oversimplifies the basin fill. All early basin boundaries are not necessarily faults, as many are onlap unconformities. Similarly, all late-phase basin limits are not low relief unconformities, as at least locally there are major faults. MacCutcheon and Robinson (1987) concluded that strike-slip faulting in the pull-apart basin model of Bradley (1982) was an unlikely mechanism for the formation of the Maritimes Basin. They proposed that overthrusting and crustal thinning related to the Acadian Orogeny produced isostatic adjustment, rapid subsidence and block faulting in the Late Devonian to Early Carboniferous. This phase was succeeded by slower thermal subsidence through the Late Carboniferous to Early Permian.

Kingston *et al.* (1983) proposed a global basin classification scheme based on plate tectonic settings and mechanisms causing basin subsidence. It is generally accepted that the Maritimes Basin was formed on the continental crust in an area of convergent plate movements (emplacement of the Meguma Terrane) near the plate margin but away from a subduction zone (Keppie, 1988). Using the criteria of Kingston *et al.* (1983) the Maritimes Basin can be classified as a Continental Wrench (CW) or Latera 1 Basin (LL) (Fig. 5-26).

In cross-section the Maritimes Basin resembles the Malay Basin (Fig. 5-27) because it is situated away from the volcanic arc area at the interior of the plate, and is dominated by wrench or shear structures. Figure 5-27 is a generalized cross-section of the Maritimes Basin in a three-stage sequence similar to that proposed by Kingston *et al.* (1983) for an idealized Lateral Basin; episodic shear and/or wrench events or oblique compression have modified the basin features. It is to be expected that different parts of the Maritimes Basin were affected to varying degrees by one or both of these mechanisms. Furthermore, all events may not be equally represented in terms of style or intensity. For example, a wrench fold belt may closely resemble the configuration of thrusted Carboniferous strata in the St. John area of New Brunswick (Nance and Warner, 1986), whereas the Cumberland Basin may be weakly to moderately affected by episodic wrench events.

Although the two-part tectonic development of the Maritimes Basin proposed by Bradley (1982) generally explains the local (proximal) versus the external (distal) source for basin-fill material within the Maritimes Basin, it does not adequately explain local basin variations, particularly the allocycles of Carboniferous sedimentation within the Cumberland Basin. In the Tatamagouche area of the Cumberland Basin, three episodes of rapid subsidence (or uplift) are recorded by thick fanglomerates in the Devonian, Namurian, and early Westphalian B. Each fanglomerate facies is succeeded by onlapping fluvial and/or marine facies, which may represent sedimentation during deceleration of subsidence in the basin (Ryan *et al.*, 1987).

The structure of the southwestern part of the Maritimes Basin is dominated by northeast-southwest faults. This pattern is disrupted by the east-west Cobequid - Chedabucto Fault System. In southern New Brunswick, where this complex fault zone merges with northeast-trending structures (Caledonia Highlands Massif and related faults), a highly complex fault and fold belt has been formed (Gussow, 1953; Ruitenberg and McCutcheon, 1982; Nance and Warner, 1986).

The east-west Cobequid Highlands Massif probably behaved as a fault-bound wedge which was tilted in response to strike-slip movement (cf. Fralick and Schenk, 1981) and flexure (Fig. 5-27). This in turn may have been due to resistance to thrusting in southern New Brunswick. The result was allocyclic sedimentation within the Upper Devonian to Lower Permian strata of the Cumberland Basin (Ryan *et al.*, 1987).

If this pattern is the result of westward transform movement along the Cobequid - Chedabucto Fault System and en echelon faults, as implied by Keppie (1982b), then the episodes of rapid basin subsidence or source area uplift and subsequent slower, regional subsidence may be the result of the same tectonic mechanism. Alternating periods of transpressional flexure and rapid subsidence by downward block faulting and tilting due to strike-slip movement along the faults, resulted in allocyclic sedimentation within the Cumberland Basin. Motion on the northeast-trending faults through southern New Brunswick and extending into the Gulf of St. Lawrence (Magdalen Basin) has several interpretations. The most recent work by McCutcheon and Robinson (1987) and Durling and Marillier (1990) indicate minor strike-slip (post-Horton and pre-Windsor) movement on the Belleisle Fault. It, therefore, was unlikely to be a master fault for the pull-apart interpretation of the Magdalen Basin proposed by Bradley (1982).

The Maritimes Basin can be classified in general terms as a continental wrench basin caused by flexural subsidence and fault block tilting occurring in response to strike-slip movements along the suture zone between the Avalon Composite Terrane and the Meguma Terrane.

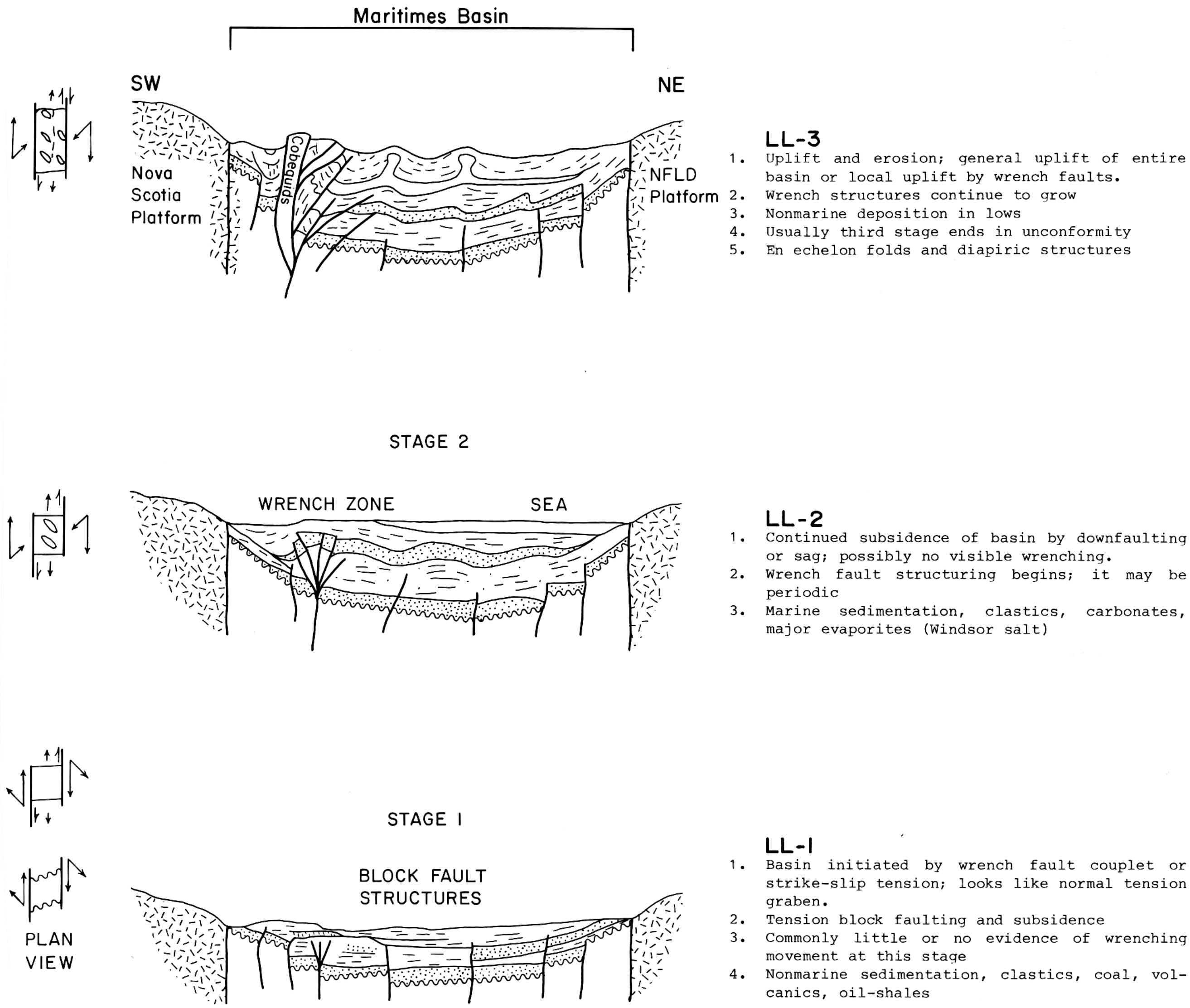


Figure 5-26. Tectonic evolution of the Cumberland Basin, an example of a lateral wrench basin.

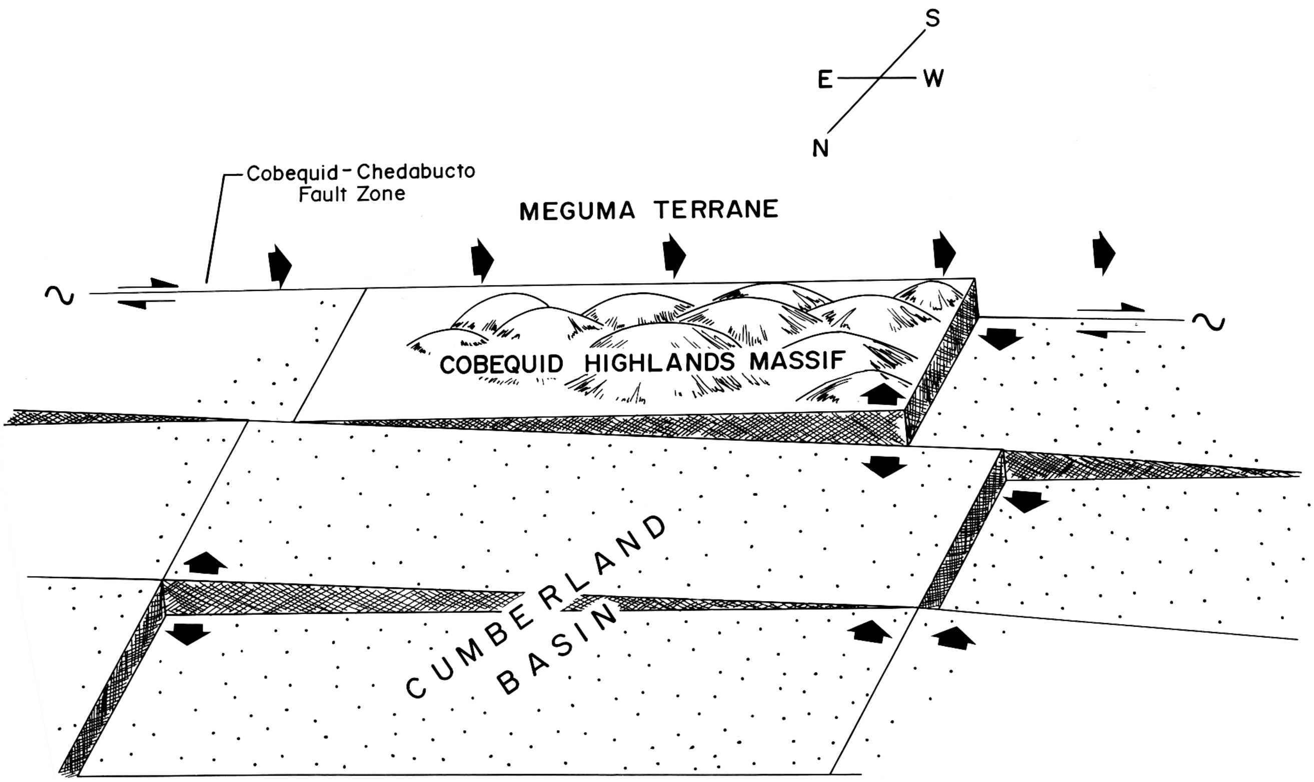


Figure 5-27. Perspective diagram illustrating the general structural setting of the Cumberland Basin adjacent to, and parallel with, the Cobequid - Chedabucto Fault System and the Cobequid Highlands Massif, and the resulting complexity related to block tilting in a lateral wrench basin environment.