GEOLOGICAL SURVEY OF CANADA

OPEN FILE 4678

Regional Geology and Hydrogeological Potential of the Triassic/Jurassic Fundy Group, Annapolis-Cornwallis Valley, Nova Scotia

A.P. Hamblin

2004

Available from
Geological Survey of Canada (Calgary)
3303 33rd Street N.W.
Calgary, Alberta T2L 2A7

Hamblin, A.P.

2004: Regional geology and hydrogeological potential of the Triassic/Jurassic Fundy Group, Annapolis-Cornwallis Valley, Nova Scotia; Geological Survey of Canada, Open File 4678.

INTRODUCTION

Triassic/Jurassic Rifts of Eastern North America

Eastern North America includes the classic Atlantic-type passive continental margin formed by the Middle Jurassic breakup of the supercontinent of Pangea. However, before that momentous event occurred, there was an earlier, less successful, phase of extension recorded by the deposition of rocks of the Early Mesozoic Newark Supergroup. The Triassic/Jurassic rocks of onshore Atlantic Canada are mainly red continental clastic sediments, tholeiitic basalts and minor mafic dykes of Middle Triassic to Early Jurassic age, preserved in the Bay of Fundy and Chedabucto Bay areas. These rocks were first described by Jackson and Alger (1829) and have received only periodic and modest attention since. They are related to the early stages of rifting and drifting that led to the opening of the proto-Atlantic Ocean, and unconformably overlie a variety of Paleozoic rocks which themselves relate to earlier collisional and extensional phases (Greenough, 1995; Wade et al., 1996). They are the result of a phase of incipient rifting of Pangea and preserve a record spanning more than 30 million years.

During the Late Paleozoic, most of the existing cratonic masses had been tectonically assembled into the massive Supercontinent we refer to as Pangea, centred over the paleoequator. The Bay of Fundy area was well within the interior of that complex. During the Late Permian and Early Triassic large regions of this complex, including eastern Canada, were uplifted causing widespread erosion of the deformed Paleozoic successions. Global eustatic sea level was probably lower during Triassic time than at any other time during the Phanerozoic, except the present, but eustatic sea level was less influential on Triassic rift basin sedimentation than was regional tectonism (Lorenz, 1988). As Pangea began to break up, a period of lithospheric extension and collapse ensued during the Middle to Late Triassic, and the Triassic extensional rift system of eastern North America was born (Fig. 1) (Brown and Grantham, 1992; Greenough, 1995; Wade et al., 1996). This is represented by an enormous series of rift basins formed along a wide zone extending from the future Gulf of Mexico through Nova Scotia, Morocco, the Tethyan margin, western Europe, Greenland and Spitzbergen (Olsen, 1997). These basins developed along a series of compressional suture zones which were converted to extensional décollements during the break-up phase. The ultimately successful rifting, drifting and creation of the Atlantic oceanic basin was eventually accomplished in Middle Jurassic time (and continues today) along a rupture hundreds of kilometres to the east when North Africa separated from North America, leaving part of itself stranded behind in Nova Scotia.

Acknowledgements

Steve Grasby and Christine Rivard reviewed an earlier version of this manuscript and provided suggestions for improvement. Paul Wozniak compiled and drafted the figures.

GENERAL TECTONIC AND DEPOSITIONAL SETTING

Regional Appalachian Tectonic Setting

The Northern Appalachian Orogen is an elongate northeast-southwest belt of deformed rocks on the eastern seaboard of North America. The upper crustal rocks of Atlantic Canada have been divided into five main tectonostratigraphic zones, or "composite suspect terranes" by Williams (1979) and Williams and Hatcher, (1982), which were acquired by the North American craton over a long, complex tectonic history. Mainland Nova Scotia is composed of two of these: the Avalon and Meguma Terranes. The Avalon Terrane, which consists of thick Proterozoic sedimentary and volcanic rocks overlain by Cambro-Ordovician shallow-water clastics, was accreted to the North American craton during the Acadian Orogeny and amalgamation of Pangea (Williams, 1984; Keppie, 1982). It occupies much of mainland Nova Scotia north of the Cobequid-Chedabucto Fault. South of that fault zone are very different rocks of the Meguma Terrane, consisting of thick Cambrian to Lower Devonian marine clastic rocks of North African affiliation. This terrane was sutured to the Avalon Terrane along the high-angle, deep-crustal fault zone, the Cobequid-Chedabucto Fault (or "Minas Geofracture" of Brown and Grantham, 1992), extending to depths of 20 km or more (Wade et al., 1996). This fault, one of the most prominent in Atlantic Canada, had a protracted history of dextral and sinistral strike-slip motion, also involving phases of dip-slip motion. The main phase of Alleghanian compressional deformation is manifested in Nova Scotia as middle to late Carboniferous dextral oblique transpression along various faults, including the Cobequid-Chedabucto Fault which separates the Meguma and Avalon Terranes along the north shore of the Bay of Fundy. The Meguma Terrane, a small slice of Africa, was later left behind in Nova Scotia when successful Atlantic rifting separated Africa from North America. However, in mid-Triassic to Jurassic time, the region was dominated by an extensional regime associated with the initial phases of opening of the proto-Atlantic Ocean.

This extensional regime reactivated previous compressional sutures, promoting major dip-slip subsidence in Nova Scotia, primarily along the Cobequid-Chedabucto Fault (Wade et al., 1996). The Fundy Rift System evolved through four major phases, as follows. I) Late Devonian-Late Carboniferous Acadian and Alleghanian thrusting events which assembled the Avalon and Meguma Terranes by collisional orogenesis along the trace of the modern Cobequid-Chedabucto Fault, and deposition of the Horton, Windsor and Mabou groups marine/continental deposits in an Early Carboniferous rift, II) Late Carboniferous-Middle Triassic deposition of the thick red fluvial clastic sediments of the Pictou Group, followed by local erosion, III) Middle Triassic-Early Jurassic development of the Fundy Rift, due to tectonic relaxation and subsidence of the Meguma terrane down the Cobequid-Chedabucto Fault décollement resulting in a deep fault-bounded basin, which filled with synrift continental sediments and basaltic volcanics of the Fundy Group, and IV) Early Jurassic-Recent further extension, subsidence and accumulation of younger deposits, followed by erosion (Brown and Grantham, 1992).

Absaroka Sequence

In the Fundy region, the uneroded remnants of the Kaskaskia Sequence of Sloss (1963) are represented by the inverted, deformed and eroded Horton, Windsor and Mabou Groups, which are present beneath the Bay of Fundy area. Renewed emergence of the Canadian Shield craton and stripping of hundreds of metres to kilometres of older sedimentary cover had peneplaned the craton, before subsidence again allowed accumulation of sedimentary deposits (Sloss, 1988). Middle Triassic- Early Jurassic strata have traditionally been included in the latest portion of the Absaroka Sequence (Late Carboniferous to Early Jurassic) of Sloss (1963), the longest and most complex of the Phanerozoic tectonostratigraphic subdivisions (Sloss, 1988). In the Fundy region, thick fluvial redbeds deposited during Absaroka I and II (latest Carboniferous to Late Permian Pictou Group, preserved elsewhere) were eroded before Middle Triassic rifting began. The Middle Triassic-Early Jurassic Absaroka III extensional basins enclosing the Fundy Group, rest on a regional unconformity, and continue the motif of deposition dominated by fluvial redbeds. However, from a tectonostratigraphic perspective, these strata are more closely related to the following Zuni Sequence, the record of the opening of the Atlantic.

Regional Triassic Stratigraphy

Middle Triassic-early Jurassic rocks of eastern North America have been assigned to the Newark Supergroup, a catch-all time-stratigraphic term meant to unify the diverse stratigraphic nomenclatures of the many similar and coeval half-graben deposits of the Appalachian Orogen from South Carolina to Nova Scotia (Klein, 1962). Strata of the Newark Supergroup typically display the tripartite stratigraphy typical of nonmarine extensional basins: basal fluvial deposits, overlain by intermediate lacustrine deposits, overlain by upper fluvial sediments, reflecting the general tectonic evolution of rifts from broad sag subsidence to syn-rift maximum subsidence, to waning subsidence (Arguden and Rodolfo, 1986; Hamblin and Rust, 1989; Olsen, 1997). Newark Supergroup basins are of two types, dependant on a complex interplay of tectonic subsidence, climatic/hydrologic conditions and sediment supply. Many were hydrologically-open and dominated by coarser grained fluvial deposits suggesting through-going drainage patterns and with little evidence for large deep lakes (eg. Fundy Basin) (Nadon and Middleton, 1985; Olsen 1997). Others were hydrologically-closed and dominated by the fine grained deposits of deep, permanent lakes with strong cyclicity, and lesser basin-margin coarse deposits (eg. Newark Basin) (Van Houten, 1964; Olsen, 1997). This Supergroup comprises six approximately coeval groups which have been formally defined in different basins: each of the half-graben includes only one group. Hence, all strata of the Fundy Basin Rift are included only in the Fundy Group.

Rift Basin Basics

To understand the geology of the Fundy Rift it is necessary to first review the basic characteristics of all rift basins. Research, exploration and understanding of the structural controls, sedimentary successions and resource potential of rift basins has progressed rapidly over the past fifteen years. This was spurred initially by the recognition of lacustrine mudstone as a common, excellent hydrocarbon source rock, and that the half-graben structural unit is the fundamental building block of all rifts. The realization that rifts contain 5% of the world's sedimentary volume, but 10-20% of the world's hydrocarbon resource (to say nothing of sediment-hosted metallic minerals, industrial minerals, and groundwater resources) fuelled an unprecedented international effort to understand these closed and confined basins, through comparative studies of modern and ancient examples.

The typically thick sedimentary section is directly linked to tectonic events in a steady state feedback process and displays geologically instantaneous reaction to those controls. Depositional environments directly "feel" the basin margin and structural events more than in most marine settings. Tectonism controls sedimentation by its influence on basin geometry and asymmetry, uplift/subsidence and erosion rate, topographic gradient, and subsequent thermal and deformational effects (Steel, 1976). Sedimentation rates are generally high due to the large topographic relief (causing rapid erosion) and internal drainage into a relatively confined depocentre (causing rapid fill). However, if subsidence is particularly rapid or continuous there could be periods of sediment starvation and slow deep-water deposition (Pitman and Andrews, 1985). Because tectonic phases commonly vary in intensity and episodicity, the sedimentary record commonly displays distinct packaging and trends (Steel et al., 1978). In addition to tectonic controls, Manspeizer (1985) suggested that a large fault-bounded basin can create secondary climatic influence as rain shadow and adiabatic air flow effects, resulting in a more arid intrabasinal climate.

Transtensive basins, those dominated by strike-slip motion during sedimentation, are generally small and poorly preserved due to later deformation which is commonly extreme. Most importantly, they are typified by great apparent stratigraphic thicknesses of the same order of magnitude as the basin size, and 2-5 times the actual basin depth. This is possible because the sediment bodies are stacked *en echelon* lengthwise along the basin due to the dominantly lengthwise horizontal component of structural motion during extension. As this motion represents the effective definition of transtension, the accompanying sedimentary style is the key to justifying such an interpretation. Transtensive basins have a ceratin set of characteristics, which are not demonstrated by the Fundy Group, and this tectonic style is rejected as a fruitful concept for interpretation of the Fundy.

Distensive (as opposed to transtensive) rift basins (graben) are typically large (100's km long x 10's km wide x several km deep) and long-lived (10's Ma). They are associated with crustal thinning, mantle upwelling, high heat flow and some volcanism (Neugebauer, 1983). Linear isostatic shoulder uplifts rim the grabens due to unloading and rotation of the footwall as the hanging wall subsides (Gawthorpe, 1987) and provide local sediment sources but also direct most of the runoff away from the graben (Frostick and Reid, 1987). Recent seismic studies (Gibbs, 1984; Bosworth, 1987; Frostick and Reid, 1987; Rosendahl et al., 1986; Coletta et al., 1988) indicate that virtually all rifts are asymmetric in geometry. Listric bounding faults merge at 12-18 km depth along a major mid-crustal décollement surface which separates upper brittle and lower ductile layers (Brun and Choukroune, 1983). In plan view the major bounding faults are curved and occur on one side only, although there may be smaller antithetic faults on the other side which give a surface form of symmetry to the basin (Gibbs, 1984; Frostick and Reid, 1987; Coletta et al., 1988; Ellis and McClay, 1988). Once initiated, block rotation subsidence on listric faults and compensating shoulder uplift offset the pre-graben shallow depression or domal uplift. Through time the displacement is localized onto fewer faults and the narrow graben development is actually a late-stage response (Girdler, 1983; Morgan and Golombek, 1984; Clendennin et al., 1988). The hinged hanging wall slope may be represented by a monoclinal ramp (tilt-block/half graben of Leeder and Gawthorpe, 1987) or by a series of stepped antithetic fault blocks (Crossley, 1984).

In distensive rift basins the overall basin-fill is large and linear (100's km long x 10's km wide x several km thick) and rests unconformably on basement rocks. Because virtually all tectonic motion is vertical, there is a vertical stacking of basinwide stratigraphic units which correspond to major tectonic phases (McKenzie, 1978). There should be some lengthwise consistency in the stratigraphic record, although segmentation of individual sub-basins could introduce variation in detail, and many sedimentary features are spatially dependant (Rosendahl et al., 1986; Leeder and Gawthorpe, 1987). Intracontinental bimodal volcanics are commonly extruded in the early history, especially close to bounding faults. The overall basin-fill sequence typical of distensive basins can be summarized from several studies (Triassic of circum-Atlantic, Arguden and Rodolfo, 1986; Martini et al., 1986: Cretaceous/Tertiary of China, Li et al., 1982; Watson et al., 1987) and is generally preserved in stable intracratonic areas with moderate deformation. The sequence comprises a) bimodal volcanics, b) coarse subaerial fluvial sediments in a broad sag basin, c) narrow graben (syn-rift) sequence of subaqueous followed by subaerial deposits, d) overlying (post-rift) sequence of thermal subsidence phase.

Within each basin the syn-rift sequence has a wedge shape, thickening toward the footwall scarp (Frostick and Reid, 1987). Each segment displays a marked basinwide asymmetry in facies and thickness (Van Houten, 1965; Ryder et al., 1976; Leeder and Gawthorpe, 1987) and the polarity of this asymmetry alternates along the length of the system (Crossley, 1984; Leeder and Gawthorpe, 1987). Depositional processes and facies arrangements in each segment are similar but may not be exactly the same or exactly synchronous (Rosendahl et al., 1986). Most fault-bounded intracontinental basins are elongate parallel to structural grain, and sedimentation occurs in internal drainage systems involving both transverse and longitudinal components. A common suite of facies includes a) proximal coarse grained alluvial fan and fluvial deposits, b) medial sandy fluvial and shoreline deposits, c) distal fine grained lacustrine deposits (Miall, 1981; Reading, 1986). Asymmetry of facies distribution is common, with alluvial fans marking the footwall fault margin, fluvial and shoreline deposits characterizing the hangingwall ramp margin, and lacustrine deposits distinguishing the basin centre (as described by Van Houten, 1965; Ryder et al., 1976; Link and Osborne, 1978).

Lake Malawi provides a modern example of a distensive basin from the west African Rift (Crossley, 1984). Alluvial fans occur on the steep fault margin, whereas major floodplains and river deltas characterize the ramp slope margin; an asymmetry which alternates along the length of the lake in segments 100-200 km long x 50-75 km wide. The hanging wall slope is a monoclinal ramp or a series of stepped fault blocks on which the dominant sediment input is spread over a wide area, and in places is trapped in small fault-bounded mini-basins. An arid seasonal climate gives flashy runoff, little vegetation, episodic high volumes of sediment input and an anoxic stratified lake. Strong southerly winds produce consistent longshore redistribution of sediment. The Triassic of the circum-Atlantic area provides an ancient example of continental sedimentation in arid distensive basins (Arguden and Rodolfo, 1986; Van Houten, 1965; Martini et al., 1986; Nadon and Middleton, 1984). A tripartite stratigraphy is present in most basins with moderate thicknesses an order of magnitude smaller than the basin size. The Newark Basin is 220 km long x 75 km wide and contains 7.5 km of sediment. The sequence is a) basal thick alluvial/fluvial conglomerate and sandstone, b) middle lacustrine shale, siltstone and sandstone, and c) upper reddened fluvial/alluvial sandstone, conglomerate and siltstone. Internal smaller-scale sequences are common and may relate to tectonic motions or climatic phases.

The main control on sedimentation in distensive rift basins is a complex interplay of sediment input, tectonic slopes and topography created by faulting and block rotation, and relative lake level affected by subsidence and climatic cycles. The fault-induced tectonic slopes and topography influence all gravity-driven sedimentary processes at basin margins and on basin floors (Leeder and Gawthorpe, 1987). After fault motion the elevated steep footwall scarp drains a very small area due to shoulder uplift and will initially produce small, thick alluvial fans with limited lateral extent (Rosendahl et al., 1986; Frostick and Reid, 1987; Leeder and Gawthorpe, 1987). That margin is characterized by narrow belts of coarse marginal facies, axial lacustrine sediments and abrupt vertical and lateral changes in facies and thickness (Gawthorpe, 1987). Over time, as erosion of that elevated scarp proceeds, this side of the sub-basin provides a larger volume of sediment (Leeder and Gawthorpe, 1987; Blair and Bilodeau, 1988). The flexural, hinged hanging wall ramp drains a large area, the slope of which increases during active subsidence. This side of the sub-basin is characterized by extensive fluvial/deltaic systems which build into the shallow lacustrine setting (Rosendahl et al., 1986; Frostick and Reid, 1987), depositing broad belts of deltaic and shallow lacustrine facies with gradual changes in facies and thickness (Gawthorpe, 1987).

Each fault subsidence event has an instantaneous deepening effect (Blair, 1987) causing shoreline transgression at both the steep footwall and gentle hanging wall margins, and soft-sediment deformation (Leeder, 1987). Therefore, the lacustrine facies dominate only during periods of maximum subsidence which create topographically deep, closed sub-basins, and dominate especially near the steep footwall side (ie. axis) of the asymmetric half-graben segment (Blair, 1987; Leeder and Gawthorpe, 1987; Watson et al., 1987). As discussed by Blair and Bilodeau (1988), and contrary to some conventional wisdom, thick fine grained sediments denote the maximum phases of active subsidence in a fault-bounded basin. This concept is based on a) the disparity between rapid rate of response to tectonic subsidence and creation of topographic relief versus the slow rate of erosion and coarse sediment production (8 to 117 times slower) from high relief fault scarps, b) the instantaneous response of fine grained environments to tectonic subsidence versus the slow rate of response of coarse grained environments, and c) various observable modern examples (eg. Death Valley, Red Sea) which commonly have low gradient fluvial/lacustrine environments close to the active fault margin where subsidence is focussed, and very restricted coarse grained fans and braidplains (Blair and Bilodeau, 1988). Therefore supply of coarse sediment always lags behind fault-induced subsidence. But as subsidence decreases, scarp erosion and sediment supply catch up, coarse marginal facies prograde from the sides, and a general coarsening-upward sequence develops (Blair, 1987; Watson et al., 1987; Blair and Bilodeau, 1988).

Fundy Basin Rift

Nine major Triassic rift basins are preserved onshore in an arcuate curve along the Appalachian Orogen, from South Carolina to Nova Scotia, along with numerous smaller basins (Manspeizer, 1981; Brown and Grantham, 1992) (Fig. 2). The Fundy Rift is the largest (14,000 km^2) and northern-most exposed of these. This northeast-trending rift system was initiated during the opening phases of the proto-Atlantic Ocean by the breakup of the Pangean Supercontinent, and generally owe their existence to the Triassic-Jurassic extensional reactivation of pre-existing compressional thrust faults and ramps that had formed during the earlier Acadian and Alleghanian Orogenies (Manspeizer, 1981, 1988; Withjack et al.,1995; Wade et al., 1996; Tanner, 2000). The North Atlantic opened, from south to north like a zipper, with the northern portions last (Greenough, 1995). This NW-SE directed extension reactivated NE-trending

Paleozoic compressional boundary faults as listric normal faults, forming the northwestern boundary faults of the Fundy Basin (Withjack et al., 1995). Most of these basin are half-graben, bordered by one major basin-bounding fault which delineated the surface trace of a seaward-dipping detachment zone, and a relatively undeformed hinged margin (Manspeizer, 1988). Each preserves thousands of metres of continental sediments and basic volcanic rocks, deposited over a period of about 45 million years (Brown and Grantham, 1992).

Most Triassic rift basins of eastern North America include a standard stratigraphic succession of three sedimentary facies assemblages (Manspeizer, 1981), which delineate an overall fining-upward sequence, and are distributed asymmetrically within the basin. These are 1) coarse boulder conglomerates and sandstones adjacent to the footwall border fault, deposited in alluvial fan and fan-delta complexes, 2) medium to coarse sandstones and conglomerates on the opposite side of the half-graben, deposited in braided fluvial and aeolian settings, dispersed from the hanging wall ramp, and 3) red mudstones and siltstones with paleosols or dark grey laminated mudstones, in the central basin area and near the master fault, deposited in playa or lacustrine settings, respectively.

In Fundy Basin, the master fault forms the northern/northwestern margin, where proximal facies are concentrated, and the north-dipping hinged hanging wall forms the southern/southeastern margin, typified by more distal facies. Facies projections suggest the probability that lacustrine sequences are widespread beneath the Bay of Fundy, along the basin axis, near the footwall fault margin (Wade et al., 1996). The Fundy Basin was located very near the Triassic paleoequator (about 10-20°N), near the centre of the enormous Pangean supercontinent (Fig. 1), and this position (and the concomitant paleoclimate) profoundly affected depositional styles and facies present (Wade et al., 1996).

These rocks are well exposed in outcrop along the Fundy shores of New Brunswick and Nova Scotia, at Chedabucto Bay in Nova Scotia, and in two wells drilled offshore in the Bay of Fundy (Nadon and Middleton, 1985; Brown and Grantham, 1992; Wade et al., 1996; Tanner and Brown, 1999). They dip gently toward the master fault, in Fundy that is toward the north at about 6° (Manspeizer, 1981; Hubert and Forlenza, 1988). The Fundy Basin represents a half-graben located at the boundary between the Avalon and Meguma Terranes and deposition was controlled by subsidence along the Cobequid-Chedabucto Fault. The Fundy Basin covers an area of about 16,500 km^2, primarily beneath the waters of the Bay of Fundy : petroleum exploration programs between 1968 and 1983 resulted in acquisition of 4600 km of seismic data and two deep wells in the Bay (Wade et al., 1996).

The Fundy Group of Nova Scotia/New Brunswick displays many of the important characteristics associated with distensive systems. The entire depositional area of the Fundy is large (over 300 km long and 50 km wide), and the sediments have suffered only moderate deformation over 200 Ma of subsequent history. There is no identifiable strike-slip component of syn-sedimentary fault motion in Fundy deposits. The stratigraphic units of the Fundy Group are laterally persistent, approximately synchronous and stacked vertically. There is no evidence of systematic lateral translation of sediment sources, and facies distributions and paleocurrent data are easily related to vertical subsidence phases and stationary sediment sources. In comparison to its geographic area, the Fundy Group has a small total stratigraphic thickness (2-10 km), an order of magnitude less than the general sub-basin dimensions (Fig. 3). The basin appears to have had a long-term asymmetric structural development and consequent asymmetric facies distribution consistent with the half-graben geometry typical of distensive rift segments. Within the basin, the locations of steep footwall scarp and hanging wall ramp remained constant throughout the period of fault-induced subsidence. The Fundy Group is therefore interpreted to represent deposition in part of a distensive or rift graben tectonic system.

THE FUNDY GROUP

Introduction

The Fundy Group was defined by Klein (1962) to include the Triassic and early Jurassic reddish clastic sediments, plus the interbedded dark grey basalts present in the Bay of Fundy area which overlie Paleozoic rocks, with angular unconformity. In Nova Scotia, this third-order, unconformity-bounded sequence comprises in ascending order, the Wolfville, Blomidon, North Mountain, Scots Bay and McCoy Brook formations (Fig. 4), and is similar to the original "Newark Group" of Powers (1916). In New Brunswick, it comprises in ascending order, the Honeycomb Point, Quaco, Echo Point and Lepreau formations: to some extent, these formations intertongue, especially near basin margins (Klein, 1962; Nadon and Middleton, 1985). The upper boundary of the Fundy Group is truncated by a regional erosional unconformity, which removed up to 2 km of strata from the basin over the last 175 Ma (Wade et al., 1996). Wade et al. (1996) provided an excellent review of the geology and considerable petroleum potential of the Fundy Group strata in the Fundy Rift.

In sequence stratigraphic terms, the Fundy group comprises four fourth-order unconformity-bounded tectonostratigraphic sequences (Olsen, 1997). In Nova Scotia, these are, in ascending order:

A) TS I discontinuously distributed initial synrift strata of Anisian age of red alternating fluvial and aeolian sandstones with minor red lacustrine mudstone up to about 50 m thick, the basal beds of the Wolfville Formation;

B) TS II wedge-shaped sequences of early synrift strata of Ladinian to late Carnian age of red fluvial sandstones and siltstones in 2-10 m fining-upward cycles, with possible lacustrine mudstone sequences identified on seismic near the border fault, all belonging to the Wolfville Formation;

C) TS III thick and widespread middle synrift strata of late Carnian to Late Rhaetian age, of red fluvial/aeolian sandstones with minor mudstone, overlain by a thick succession of stacked red mudstone cycles with minor sandstone deposited on extensive playa mudflats belonging to the uppermost Wolfville and Blomidon Formations, and approximately coeval with the very thick organic-rich lacustrine mudstone sequences of the Newark Basin in the US;

D) TS IV thick and widespread late synrift strata of Late Rhaetian to Hettangian age, comprising a complex succession of minor red and black mudstones, dark green tholeiitic subaerial lava flows, overlain by grey and red lacustrine and fluvial mudstone, sandstone and limestone, belonging to the uppermost Blomidon, North Mountain, Scots Bay and McCoy Brook formations. The Triassic-Jurassic boundary occurs in the upper Blomidon, and the North Mountain basalts have been dated at about 201-202 Ma.

Distribution and Thickness

In Nova Scotia, rocks of the Fundy Group outcrop in the Annapolis-Cornwallis Valley, the Minas Lowlands, along North Mountain and in Chedabucto Bay. In New Brunswick, they crop out at Grand Manan, Point Lepreau, St. Martin's and Waterside (Nadon and Middleton, 1985). The coeval Chedabucto Formation outcrops along the north shore of Chedabucto Bay, displaying similar facies to the Fundy Group (Tanner and Brown, 1999). Fundy Group rocks are present in much greater thicknesses offshore beneath the Bay of Fundy, Chedabucto Bay and Orpheus Basin(Wade et al, 1996; Tanner and Brown, 1999). Over 4600 km of seismic data of variable quality have been obtained from the offshore area of the Bay of Fundy. In the Bay of Fundy, the Irving Cape Spencer No. 1 well (offshore from Saint John, New Brunswick) and the Mobil Gulf Chinampas N–37 well (offshore from Lepreau, New Brunswick) provide limited regional stratigraphic control, but are both located close to the footwall fault margin and display much thicker sections for all units. Based on paleocurrent, thickness and projection data, Klein (1963) determined that the original extent of the Fundy Group deposits was not much beyond the current preservational edges, both to the north and to the south.

From offshore seismic data, the original total thickness of the Fundy Group may have been as much as 12 km, although the maximum preserved thickness is now 9.5 km (Wade et al., 1996). This maximum thickness is present near the northern bounding fault, the locus of maximum subsidence, and thicknesses in the Annapolis Valley of Nova Scotia are much less. The enclosed sedimentary sequence is wedge-shaped, thickening and dipping northward toward the master bounding fault (Fig. 5a). The individual depositional formations of the Group are each northwesterly-thickening wedges (Wade et al., 1996), mimicking the asymmetric wedge geometry of the half-graben basin.

Paleoclimate

The Fundy Basin was close to the paleoequator, positioned at approximately 20°N (Keppie, 1977), and the evidence suggests it was the driest (Hubert and Mertz, 1984; Olsen, 1990; Olsen, 1997). All lines of evidence suggest subaerial deposition in a warm, semi-arid paleoclimate, at the centre of the Late Triassic "hothouse" Pangea (Olsen, 1997). The Fundy Basin would have been positioned within the Northeast trade Wind Belt. Evidence for nonmarine deposition in dry conditions is abundant: the rocks are generally oxidized, characteristics suggest alluvial fan/fluvial/aeolian/mudflat/lacustrine environments, paleosols are prominent, the North Mountain basalts were extruded subaerially, playa evaporites are common accessory minerals and all paleontological remains represent terrestrial flora and fauna. Tanner (1993) interpreted a trend of increasing humidity from semi-arid to subhumid conditions during deposition of the Wolfville Formation, to semi-arid to arid conditions for the Blomidon Formation, and semi-arid to subhumid climate for the Scots Bay Formation. Extensive aeolian deposits in the Wolfville on the north side of Minas Basin may indicate periods of increased aridity (Hubert and Mertz, 1984). Correlative rocks, deposited in the offshore Orpheus Graben 300 km to the east, include thick salt units of the Argo Formation, confirming the paleoclimate interpretations (Wade et al., 1996; Tanner and Brown, 1999). Hay et al (1994) constructed detailed climatic circulation models for Triassic Pangea, suggesting extreme seasonal monsoonal circulation, strongly seasonal precipitation at coastlines, but generally arid conditions over enormous areas of the interior of the Pangean Supercontinent. A great deal of research has been conducted on the evidence for the concept of Milankovitch climate forcing in the Newark Basin, concluding that a full range of precession-related periods of lake level change was strongly evident in these deposits (Olsen and Kent, 1996).

Paleontology

Although not generally fossiliferous, fossil material is abundant in Triassic rocks in some areas, including large leaf and stem impressions, coaly partings, deep root casts, herbivorous and carnivorous reptiles, freshwater fish, invertebrates and trace fossils (Wade et al., 1996). Olsen (1988) provided an exhaustive discussion of the paleontology and palaeoecology of Newark Supergroup deposits in these basins. At the end of the Triassic, a major mass extinction in the marine realm, of unknown cause, led to the almost total extinction of the ammonites, final disappearance of the conodonts and collapse of the global reef ecosystem (Hallam, 1990). In the terrestrial realm, a contemporary mass extinction among tetrapods and floral elements is clearly recorded in the Fundy Group (Olsen, 1988; Hallam, 1990).

Age

A Mesozoic age for rocks in the Fundy region was first established by Powers (1916), and Baird (1972) confirmed the Triassic age of the Wolfville Formation using pelecypods, fish and reptile remains. Early Mesozoic rocks in the Fundy Rift apparently range from early Middle Triassic (Anisian) to earliest Jurassic (Sinemurian) age, primarily based on pollen and spore data, and vertebrate bones and footprints (Brown and Grantham, 1992; Greenough, 1995). This is the most extensive and continuous record in the Newark Supergroup. Fossil data from the Wolfville and Blomidon formations yield Middle to Late Triassic ages (Ladinian/Carnian/Norian) (Greenough, 1995). The basalt flows of the North Mountain Formation are dated to approximately the Triassic-Jurassic boundary (205 Ma) (Brown and Grantham, 1992) and yield U-Pb zircon dates of about 201 ± 2 Ma (Dunning and Hodych, 1990), or 202 ± 2 Ma (Hodych and Dunning, 1992). These dates suggest that the basalt flows, and the overlying Scots Bay/McCoy Brook formations are earliest Jurassic (Hettangian/Sinemurian) in age.

Post-depositional Deformation

Whereas much of the sedimentary and depositional characteristics of the Fundy Group relate directly to syn-depositional reactivation of earlier faults and subsidence of the rift basin, Mesozoic rocks were also affected by post-depositional tectonic forces (Fig 5b). Keppie (1982) and Swift et al. (1967) pointed out the importance of Mesozoic sinistral strike-slip motion and reverse faulting and folding, primarily along east-west trends. All Mesozoic rocks have been faulted as a result of, yet another, post-Triassic reactivation of the Cobequid-Chedabucto Fault (Greenough, 1995), and the pervasive development of small, north-dipping antithetic faults along the southern margin of the basin (Wade et al., 1996). Gentle to open folds, with east-west trends and wavelengths of a few kilometres, affect all Mesozoic rocks and are superimposed on the larger synclinal structure of the Fundy Rift (Greenough, 1995). These may partly be syn-depositional and partly post-depositional.

STRATIGRAPHIC AND SEDIMENTOLOGIC SUMMARY

Wolfville Formation

Definition The Wolfville Formation was originally defined by Powers (1916) and revised by Klein (1962), with a type area on the west shore of the Minas Basin at the mouth of the Avon River, from Kingsport north to Paddys Island. It comprises reddish thickly bedded medium to coarse grained arenitic to subarkosic sandstone, with subordinate peblly and conglomeratic units whose clasts are derived from the adjacent metamorphic and granitic highlands. Large-scale cross bedding is present in some locations. Deposition occurred in alluvial fan, fluvial and aeolian environments, and an overall fining-upward succession is evident (Tanner, 2000). It can be traced laterally for 240 km northeastward along the Annapolis Valley from St. Mary's Bay to Truro and for 60 km westward from Truro to Economy Mountain. Coastal outcrops are generally good, although inland, exposures are rare (Taylor, 1969; Smitheringale, 1973). The Wolfville Formation is present in the two offshore wells in the Bay of Fundy. It unconformably overlies the Lower and Upper Paleozoic rocks which form the deformed basement in the area and thicknesses up to 833 m are reported (Crosby, 1962; Taylor, 1969). Wolfville rocks are conformably overlain by the Blomidon Formation. They are assigned a Late Triassic (Carnian to Norian) age.

Sedimentology The Wolfville Formation is remarkable for its heterogeneity and consists of reddish thick bedded, crudely-stratified, medium to coarse grained clastic rocks, typically in lenticular beds (Crosby, 1962; Taylor, 1969). It is an interbedded and intertonguing complex of red, coarse and medium grained clastic rocks of continental origin, deposited in an actively subsiding fault-bounded basin bounded by a major normal fault on the northwestern margin. Facies present include a depositional spectrum from basin margin alluvial fans to fluvial floodplains to aeolian dunes to sand/mud flats to shallow lacustrine environments. Taken as a whole, there is a tendency at any given location, for the succession to pass upward from alluvial fan to fluvial to aeolian to mudflat deposition. The strata generally dip 5-10° NW. Numerous steeply dipping normal faults and joints, striking NE/SW, displace strata of the Wolfville by a few metres, although there is no evidence for a large, basin-bounding fault on the south side of the Fundy Rift, confirming its half-graben asymmetry (Crosby, 1962; Smitheringale, 1973; Wade et al., 1996). Following are more detailed descriptions of the main lithofacies.

Alluvial Fan Conglomerate/Sandstone Alluvial fan deposits at the footwall fault margin are the most characteristic deposits of fault-bounded rift basins. Tectonics controlled the presence and location of alluvial fans in the Fundy Rift fault-bounded basin. Large-scale fining-upward sequences, of tens to hundreds of metres thickness, record an initial tectonic event followed by erosional lowering of the source area (Lorenz, 1988). Deposition on alluvial fans may be in proximal zone (poorly sorted coarse angular sieve deposits and debris flows), mid fan (moderately sorted braided fluvial and debris flow deposits) and distal fan-toe/sandflat (well sorted and graded sheetflood and playa deposits) (Lorenz, 1988). Alluvial fan deposits generally interfinger distally with and grade into fluvial, playa and lacustrine deposits.

Klein (1962, 1963) identified both A) thick bedded, cross stratified, roundstone conglomerates of pebble to boulder size with imbrication, and interbedded sandstone, especially prominent on the south side of the Bay of Fundy ("Hants facies"), with paleocurrent dispersal toward the north and the basin centre, and B) thick bedded, crudely stratified, polymictic sharpstone fanglomerates, especially prominent on the north side of the Bay of Fundy ("Gerrish facies"), with paleocurrent dispersal toward the south away from the master fault. Conglomerates are particularly common near the base of the Wolfville immediately overlying Paleozoic rocks and may comprise 10% of Wolfville rocks (Crosby, 1962; Smitheringale, 1973), although Klein (1962) suggested there was fault repetition of pebbly beds near the Evangeline Beach/Kingsport area. Gerrish facies strata are interpreted to represent proximal alluvial fan deposits, and Hants facies conglomerates are mid to distal fan alluvial/braided fluvial deposits (Klein, 1962, 1963).

Fluvial Sandstone/Conglomerate Compared to meandering stream deposits, braided stream deposits tend to be less organized, more laterally-extensive, display abundant internal scour-and-fill surfaces, are more sandstone-dominated, and have more trough and planar-tabular crossbedding (Lorenz, 1988). Sandstones and pebbly sandstones of the Wolfville are reddish to greenish, fine to coarse grained, poorly to well sorted, thick bedded and cross stratified (Klein, 1962). Cut-and-fill channelling, and lens-like beds which pinch out laterally over 10-100 m are common, as are ripples, mud cracks and parting lineation. These sandstones were deposited in primarily braided, low sinuosity, fluvial and floodplain environments, controlled by a combination of tectonics, climate and source terrane (Lorenz, 1988; Tanner, 2000).

Hubert and Forlenza (1988) performed a very detailed study of Wolfville braided stream deposits along the south shore of Cobequid Bay, where paleocurrent data showed that the pebbly/sandy rivers flowed northward and northeastward, away from the southern basin margin toward the basin centre. Overall, the Wolfville fines upward from alluvial fan conglomerates to braided river sandstone and mudstone. They identified several different facies components which occur in fining-upward sequences, 2-10 m thick, as follows: A) basal scour surface, B) thick sets of trough crossbedded conglomerate, pebbly sandstone or sandstone, C) plane bedded fine to coarse sandstone with parting lineation, sometimes lining scour surfaces, D) muddy plane bedded or ripple cross laminated sandstone, with roots and burrows, E) rare massive or laminated sandy mudstones with roots and caliche paleosols. More proximal sequences are thicker, coarser and pebble-dominated, whereas more distal ones are thinner, finer and sandstone-dominated (Hubert and Forlenza, 1988). Overbank deposits generally consist of horizontally laminated or ripple crossbedded fine sandstones and sandy siltstones, with root casts, burrows, desiccation cracks, caliche profiles and vertebrate tracks (Hubert and Forlenza, 1988; Lorenz, 1988).

Most sandstone samples are mineralogically low rank greywackes (eastern Annapolis Valley), high-rank greywackes (western Annapolis Valley), arkoses and orthoquartzites (eastern Annapolis Valley and north shore of Minas Basin), and are texturally submature to mature and subangular to well rounded (Klein, 1962; Crosby, 1962; Smitheringale, 1973). Orthoquartzites are likely derived from recycling of clean Carboniferous sandstones. Micaceous matrix ranges up to 28% and averages 3%, and sparry calcite cement ranges up to 25% and averages 10% (Smitheringale, 1973). Hubert and Forlenza (1988) found that the average composition of the framework grains of Wolfville sandstones is 53% mono-and poly-crystalline quartz, 16% feldspar, 10% quartzite rock fragments, 8% granitic rock fragments, 4% schist rock fragments, and a variety of minor rock fragments. There is a low degree of crossbed variance, suggesting a dominance of low sinuosity streams, although these may grade distally and upsection into higher sinuosity fluvial deposits (Klein, 1963; Lorenz, 1988). Paleocurrent data, from thousands of measurements, indicate that Wolfville deposits were derived directly from adjacent basement, with transport toward the basin centre (ie, from the southeast in Annapolis Valley; from the north on the north side of the Bay of Fundy), and sandstone composition varies directly with source area geology (Klein, 1962, 1963; Hubert and Forlenza, 1988). There is a suggestion of a drainage divide just east of Wolfville, whereby to the east, rivers flowed longitudinally eastward, whereas to the west, rivers flowed longitudinally westward down the Fundy Rift (Hubert and Forlenza, 1988).

Aeolian Sandstone Extensive aeolian deposits are rare in the Triassic rift basins of North America, but the Fundy Basin, where they occur at several stratigraphic levels, is famous for them. The Fundy Rift was located within the subtropical zone of persistent Northeast Trade Winds, north of the paleoequator in Late Triassic time and the presence of aeolian deposits is definitive evidence of aridity in this basin (Hubert and Mertz, 1980; Lorenz, 1988). This confirms the regional trend of increasing aridity from south to north for the basins of the Newark Supergroup (Hubert and Mertz, 1980). The aeolian deposits occurred as localized barchanoid dune fields intimately interbedded with fluvial and sand flat deposits. Development of these deposits required strong, low-variance winds and a modest, but consistent, supply of sand grains.

Aeolian sandstones compose the upper 40-50 m of the Wolfville Formation along the north shore of Minas Basin, and are identified as such by a number of characteristics. They are fine to medium grained, subrounded to rounded, frosted with moderate to very good sorting and occur in large sets of planar-tabular and trough cross beds up to 3.5 m thick, with near angle-of-repose dips (Hubert and Mertz, 1980, 1984). Barchan and barchanoid transverse dunes likely had slipfaces up to 10 m high (Hubert and Mertz, 1984). Bimodal reg surfaces, ventifacts, high ripple index aeolian wind ripples and multiple orders of truncation surfaces are all common and all characteristic of the aeolian environment (Hubert and Mertz, 1980, 1984). Paleowinds blew consistently toward the west and southwest, parallelling the basin axis (Hubert and Mertz, 1980). Finer grained interdune facies are conspicuously rare in the Wolfville (Lorenz, 1988). Occurrences of these facies, in modest thicknesses, can be expected anywhere (geographically or stratigraphically) in the Wolfville.

Blomidon Formation

Definition The Blomidon Formation was originally defined by Powers (1916) and revised by Klein (1962), with a type area on the west shore of the Minas Basin at the mouth of the Avon River, from Paddys Island north to Cape Blomidon. It is remarkably homogeneous and comprises evenly bedded red siltstone and mudstone, with minor fine sandstone. Deposition occurred in an arid mudflat/playa setting. It can be traced laterally for 150 km northeastward along the Annapolis Valley from St. Mary's Bay to Cape Blomidon and at several places along the north shore of the Minas Basin at Economy Mountain, Parrsboro and Cape D'Or. Coastal outcrops are generally good, although inland exposures are virtually nonexistent (Smitheringale, 1973). The

Blomidon Formation is present in the two offshore wells in the Bay of Fundy. It conformably overlies the Wolfville Formation and conformably underlies the North Mountain Formation. Thicknesses up to 363 m are known and the strata dip 5°NW (Crosby, 1962; Smitheringale, 1973). The Blomidon is assigned a Late Triassic (Norian to Rhaetian) age, and spans about 20 Ma of time (Mertz and Hubert, 1990).

Sedimentology The Blomidon Formation consists of pale reddish or greenish, poorly sorted mudstone, arenaceous siltstone and argillaceous fine sandstone in laterally continuous thin beds, with minor volcanic ash beds and plant fossils (Crosby, 1962; Smitheringale, 1973). Red and green colour boundaries cut across bedding, demonstrating the secondary diagenetic redox nature of the colours (Smitheringale, 1973). The hallmark of strata in the Blomidon is the repetitive cyclicity of alternating coarser and finer lithologies, arranged in coarsening- and fining-upward sequences (Hubert and Hyde, 1982; Mertz and Hubert, 1990; Tanner, 2000). The lower 20 m commonly consists of scour-based, sandy channel units (Crosby, 1962). Klein (1962) identified both A) Del Haven facies of thick bedded siltstone-dominated strata with ripples and graded bedding in the eastern Annapolis Valley, and B) the Digby facies characterized by channelization, cross bedding and ripples in the western Annapolis Valley. Klein (1962) interpreted these as the deposits of subaqueous and subaerial lacustrine environments respectively, but later workers attribute them predominantly to playa/mudflat environments (Hubert and Hyde, 1982). Flash floods in adjacent highlands flowed as sheet flows over fan surfaces onto sandflats at the fan toes (depositing sand and silt graded beds), and farther out onto playa mudflats (depositing silt and clay beds) on the basin floor (Hubert and Hyde, 1982; Mertz and Hubert, 1990). Paleoflow dispersal was away from nearby fault margins, indicating a basinal drainage pattern configuration which persisted throughout deposition of the Wolfville and Blomidon (Klein, 1963). In later Blomidon time, clay was deposited in ephemeral playa freshwater lakes inhabited by small fish and invertebrates (Hubert and Hyde, 1982). Strata are arranged into numerous 2-12 m fining-upward cycles (attributed to autocyclic channel avulsion or fault-induced subsidence on the adjacent fan), which are in turn arranged into a number of tectonically-controlled, fining-upward or coarsening-upward megacycles (attributed to rejuvenation and erosional degradation of the adjacent fault highland) (Hubert and Hyde, 1982; Mertz and Hubert, 1990). Smitheringale (1973) emphasizes that the Wolfville-Blomidon contact is time-transgressive, and that parts of the Blomidon are coeval with parts of the Wolfville. At the top of the Blomidon, dark grey, organic-rich mudstones are prominent components, just beneath the North Mountain basalts, interpreted as extensive lacustrine deposits (Tanner, 2000). The overall succession is one of long-term fining-upward, with thickness and frequency of sandstone decreasing upward (Mertz and Hubert, 1990).

Sandflat Sandstones Sandstones of the Blomidon are reddish, fine to coarse grained, poorly to moderately sorted, and texturally immature (Klein, 1962; Hubert and Hyde, 1982). Mineralogically, they include low-rank greywacke (western Annapolis Valley), arkose and orthoquartzite (eastern Annapolis Valley), with micaceous matrix averaging 8% and sparry calcite cement averaging 15%, and minor gypsum (Klein, 1962; Mertz and Hubert, 1990). Orthoquartzites are likely thin aeolian beds derived from recycling of clean Carboniferous sandstones. Sandstones are typically very thin (<10 cm), very fine to fine grained, graded, laterally continuous, plane bedded or rippled and represent only a few % of the Blomidon rock volume (Hubert and Hyde, 1982). Crusts of evaporite minerals and deep mudcracks are common (Mertz and Hubert, 1990). These are interpreted as the deposits of broad, shallow unchannelized decelerating flows on sandflats at the toes of alluvial fans (Hubert and Hyde, 1982; Mertz and Hubert, 1990). Rare 1-3 m scoured channel forms, filled with crossbedded fine to coarse grained sandstone, are known (Hubert and Hyde, 1982).

Playa Mudflat Siltstones The bulk of Blomidon rock (80-85%) is represented by reddish brown to greyish red, poorly sorted siltstone, sandy siltstone and mudstone in laterally continuous beds up to 3 m thick (Hubert and Hyde, 1982). Horizontal lamination, ripple cross lamination, convolute structure, desiccation cracks, evaporite mineral crusts, thin sandstone partings with aeolian adhesion ripples, and horizons of caliche nodules are common (Hubert and Hyde, 1982). These are interpreted as the deposits of the most distal broad, shallow unchannelized decelerating flows on playa mudflat across the floor of the subsiding rift valley (Hubert and Hyde, 1982; Mertz and Hubert, 1990). The conspicuous presence of desiccation features and incipient paleosol development and the rarity of channelized sand-filled forms is typical of playa mudflats (Lorenz, 1988). An unknown proportion of the red siltstone may represent windblown loess deposits. Minor occurrences of horizontally laminated grey or red mudstone with desiccation cracks (some with plant, invertebrate and fish fossils) are present, especially near the top of the formation, and represent the deposits of broad, shallow ephemeral playa lakes (Hubert and Hyde, 1982; Mertz and Hubert, 1990). In the distal offshore, the Blomidon Formation may include much thicker manifestations of dark, organic-rich, lacustrine mudstone, as is common in other Newark basins.

North Mountain Formation

Definition The North Mountain Formation was defined by Powers (1916), without a type section, although Petit Passage, southwest of Digby, is considered as a reference section. It comprises thick quartz-normative, tholeiitic basalt in massive, columnar and amygdaloidal flow units, with very rare thin red sedimentary units near the top. The flows were erupted in a subaerial setting onto a relatively flat surface (Kontak, 2001), and appear to have a conformable relationship to the underlying Blomidon strata. The formation can be traced laterally for >200 km northeastward along the Annapolis Valley from Brier Island to Cape Blomidon and as a series of headlands and islands along the north shore of the Minas Basin at Economy Mountain, Parrsboro and Cape D'Or. Coastal outcrops are generally good. The North Mountain Formation is present in the two offshore wells in the Bay of Fundy. It conformably overlies the Blomidon Formation and is disconformably overlain by the Scots Bay/McCoy Brook formations (Taylor, 1969). Thicknesses up to 427 m are recorded and the strata dip 3-5°NW (Crosby, 1962). Radiometric dates of 191 $\pm$ 2 Ma (K-Ar) and 202 $\pm$ 2 Ma (U-Pb) indicate an Early Jurassic (Hettangian) age (Triassic-Jurassic boundary now fixed at 208 Ma: DNAG), and all polarities are normal (Greenough, 1995). This unit represents a very brief but massive outpouring of basaltic extrusion, lasting perhaps only 600,000 years (Olsen, 1997), and there is evidence that magma migrated toward the northeast during fissure eruptions (Greenough et al., 1989). The North Mountain basalt is the northernmost occurrence of the widespread Eastern North American Dolerite Province, directly related to the early stages of opening of the Atlantic Ocean (Greenough, 1995).

Characteristics The dark grey to brown to black basalts are low-alumina types and tachylite glass is a common groundmass. Thick flows display intergranular to subophitic, fine to coarse grained textures with phenocrysts consisting of subequal proportions of augite and zoned plagioclase and minor pigeonite, set in a groundmass of glass (Crosby, 1962; Smitheringale, 1973; Papezik et al., 1988; Greenough et al., 1989). Thin flows and flow tops display intergranular porphyritic textures, with vesicular and altered characteristics (Greenough et al., 1989). A rich suite of zeolite minerals and chalcedony-filled veins occur throughout. The formation is divided informally into lower (LFU), middle (MFU) and upper (UFU) flow units, displaying a discrete stratigraphy along the entire length of the outcrop belt (Papezik et al., 1988; Greenough et al., 1989; Kontak, 2001). The massive basal LFU flow (40-185 m thick, thinning to the northeast, and with > 230 km lateral extent) represents a single extrusion event of "ponded lava", and is coarse crystalline, and columnar-jointed (Klein, 1962; Smitheringale, 1973; Greenough et al., 1989; Kontak, 2001). It forms the upland bounding the north side of the Annapolis Valley. The middle MFU is a complex stack of at least 15 intertonguing, thin, fine crystalline flows which are vesicular, amygdaloidal and highly altered (Greenough et al., 1989; Kontak, 2001). They total about 50 m thick, but thin to the southwest (Kontak, 2001). The upper, massive, phenocrysts-rich UFU (about 150 m thick) has exposure on land limited to the Digby area, but extends out into the offshore Bay of Fundy (Kontak, 2001). It is composed of two individual thick flows, the lower one columnar-jointed and the upper one massive (Klein, 1962; Greenough et al., 1989; Kontak, 2001). There are essentially no thick sedimentary beds between any of these flows, suggesting very little time between extrusive events (Papizek, et al., 1988; Greenough et al., 1989). The absence of agglomerates indicates very fluid, non-explosive eruption and abundant glassy groundmass suggests very rapid cooling and crystallization (Crosby, 1962; Smitheringale, 1973). The Early Jurassic Scots Bay and McCoy Brook formations actually overlie the MFU in their outcrop areas, further demonstrating the limited areal extent of the UFU (Kontak, 2001). Geochemical characteristics are consistent through all three units, similar to other Triassic basins and to ocean floor basalts, suggesting derivation from a mantle source below continental crust, with crustal contamination during eruption (Papizek, et al., 1988). The tholeiitic composition and large volume are the result of rapid and extensive lithospheric stretching overtop of a mantle hotspot (Greenough, 1995). Basalts on the north shore of Minas Basin are thinner and less mafic, possibly as a result of northeasterly magma migration during fissure eruption, similar to the fissure eruptions at Kilauea in Hawaii (Greenough et al., 1989). The originating fissure was located somewhere in the Digby area under North Mountain, and probably parallelled the Fundy Rift trend (Papizek, et al., 1988), but may have been as much as 300 km long (Greenough, 1995).

Scot's Bay Formation/McCoy Brook Formation

Definition The Scots Bay Formation was defined by Powers (1916), with a type section at

Eastern Broad Cove on the south shore of Scots Bay. It comprises light-coloured, thinly bedded, interbedded fine sandstone, limestone and mudstone, with chert and jasperoid nodules. It disconformably overlies the irregular upper surface of the North Mountain basalts, with a thin basaltic breccia, and is truncated by the regional surface unconformity surface (Crosby, 1962). In outcrop the unit exposes only 5-8 m of thickness in a few small structural basins along the shore (Crosby, 1962). The correlative McCoy Brook Formation (Tanner, 1996), present on the north shore of Minas Basin, is up to 180 m of red alluvial/fluvial/aeolian sandstones, conglomerates and mudstones. These facies are similar to post-basalt strata which attain thicknesses up to 369 m in an offshore well and are assumed to underlie much of the Bay of Fundy. Thus Tanner (1996) recommended use of the "Scots Bay" terminology only as a Member or facies designation to describe the thin lacustrine sequence (with hot spring deposits) immediately overlying the basalts. However, further offshore in basin centre locations, much of the post-North Mountain basalt succession may actually consist of Scots Bay lacustrine mudstone facies. The Scots Bay/McCoy Brook formations are assigned a Hettangian (Early Jurassic) age.

Sedimentology The Scots Bay Formation consists of thin bedded green and purple mudstone, red siltstone, greenish fine crystalline limestone and grey jasperoidal limestone. Lenses of iron-rich, siliceous hydrothermal tufa are prominent components at some localities (Birney et al., 1989). Hard brown sandstone occurs at the top of the outcrops. All sandstones are texturally mature to immature, mineralogically orthoquartzites, and are cemented with sparry calcite (Klein, 1962). A diverse assemblage of ostracods, charophytes, conchostrachans, stromatolites, gastropods, fish and logs are present (Birney et al., 1989). Scots Bay deposits are interpreted to represent sedimentation in a well-oxygenated lacustrine environment, with magma-heated hydrothermal, alkaline springs percolating up through volcanic vents from the underlying basaltic lavas (Klein, 1962; Birney et al., 1989). Metre-scale cyclic variations in lithology suggest periodic shrinkage and expansion of the lake which affected this nearshore setting (Tanner, 1996). These deposits are presumed to extend into the offshore area of the Bay of Fundy, but may not have had a great extent.

The coeval McCoy Brook Formation comprises predominantly redbeds of thinly interbedded muddy sandstone and sandy mudstone, with subordinate fissile fossiliferous claystone and graded beds of horizontally laminated to rippled sandstone (Tanner and Hubert, 1992; Tanner, 1996). Rare, thicker sandstone channel deposits are up to 5 m thick, have scoured bases, crossbedding and paleoflow indicators suggest braided fluvial dispersal from the adjacent basin margin toward the basin centre (Tanner and Hubert, 1992). Desiccation cracks, gypsum nodules, thick lenses of unbedded, fining-upward basaltic conglomerate, thin lenses of well sorted crossbedded orthoquartzite and fish fossils occur sporadically. These deposits also occur above the North Mountain Formation in the two wells offshore (Tanner, 1996). The strata of the McCoy Brook are interpreted to represent fluvial, sand flat, playa mudflat and minor lacustrine deposits, similar in many respects to those of the Blomidon Formation (Tanner, 1996). Lacustrine deposition was most fully developed in the basal beds of the Scots Bay and McCoy Brook formations (Tanner, 2000), and would be thickest at the basin centre rift axis, near the faulted footwall margin (Lorenz, 1988). Basaltic breccias represent cliff talus and debris flow deposits shed directly from the nearby fault-bounded footwall basin margin (Tanner and Hubert, 1992). Aeolian dunes of barchanoid style were present on the basin floor and migrated to the southwest, down the length of the valley, comparable to the general axial direction of fluvial dispersal (Tanner and Hubert, 1992).

HYDROGEOLOGY

Introduction

Annapolis-Cornwallis Valley is a long narrow lowland in Digby, Annapolis and Kings Counties, Nova Scotia. It is flanked to the south by metamorphosed Paleozoic rocks of South Mountain, and to the north by the Jurassic basalt forming the highland of North Mountain. The Valley, about 100 km long by 10-15 km wide, is largely developed on softer Triassic sedimentary rocks and Quaternary deposits (Fig. 6). Thus, the Valley is primarily a discharge area between two opposing highland recharge areas. It has an agricultural history dating back over 300 years, from when the Acadians first settled the area, and is famous for its high quality fruits, vegetables and its young wine industry. The agricultural success is due to a combination of fertile soils, a unique micro-climate which results from being nestled between the North and South Mountains and the consistent supply of high quality groundwater (Henigar et al., 1992).

Due to the gentle northward dip of 4-12° of all Fundy Group strata in the Bay of Fundy area, all stratigraphic intervals represented in the Triassic occur at surface somewhere in the Annapolis-Cornwallis Valley region. The main Triassic aquifers occur in the extensive Wolfville and Blomidon formations hydrostratigraphic units, and the thick, sandstone-dominated deposits of the Wolfville Formation represent the most important aquifer potential. The transmission of groundwater through Triassic rocks may be non-uniform and/or limited due to the regional dip, laterally discontinuous sub-units, variable aquifer quality and thick zones of fine grained lithologies in areas underlain by the Blomidon. The North Mountain Formation basalts represent the boundary of the Valley, but also represent an additional possible hydrostratigraphic unit. In all units, potential abundant fracturing may be important. Waters are predominantly calcium bicarbonate-rich, with low total dissolved solids.

Previous Work

Trescott (1968) performed a large study of the groundwater resources of the Annapolis-Cornwallis Valley, concentrating on the hydrogeology and aquifer potential of the Triassic and Quaternary deposits. Aside from some information supplied by Henigar et al. (1992), it is essentially the only published resource for understanding the hydrogeology of the area, and much of the following is summarized from this study. The Fundy Group rocks overlie the Paleozoic deformed basement with angular unconformity and dip gently toward the Bay of Fundy. Faults are present and have displaced the Fundy Group rocks in some locations. Groundwater flow in these Triassic aquifers was found to be essentially independent of that in the Quaternary surficial deposits (Trescott, 1968). All urban and rural communities of the Valley are situated above the potential aquifer bodies of the Fundy Group units.

The most important bedrock aquifers in the Valley reside in the Wolfville Formation. Most recharge is likely from the South Mountain highlands and flows northward downdip into the main aquifers. Wolfville Formation rocks vary widely in lithology, including relatively coarse grained arkoses, low and high rank greywackes and orthoquartzites deposited in alluvial fan, fluvial channel, floodplain and aeolian environments. There is an overall fining-upward trend for strata of the Wolfville Formation. Interbedding of coarse and fine grained lithologies is ubiquitous, and aquifer quality may vary over short distances, both stratigraphically and geographically. Based on a few test-wells, Trescott (1968) estimated about 55% of the rock is clean sandstone or conglomerate, whereas 45% is silty sandstone, siltstone and mudstone, but that these different facies could appear anywhere. However, the interbedded siltstones and mudstones act as local seals and ensure that water in the coarser facies is under artesian pressure. Trescott (1968) mentioned that the large ranges of grain size and sorting, as well as a matrix of quartz/mica and sparry calcite cement, all could reduce overall intergranular porosity and permeability. Sample transmissibilities ranged from 2000 to 6400 igpd/ft, and storage from 1.5 to 2.0 X 10^{-4}. He estimated that wells 200-400 ft deep should produce 100 igpm, and yields of 500+ igpm may be possible. Waters are of good quality, with elevated calcium, bicarbonate, hardness and alkalinity. Dissolved iron may be a problem in some areas. A test well drilled at Spa Springs (a famous 19th Century resort for the wealthy) obtained flows of 145 m^3/d from sandstones of the Wolfville Formation (Henigar et al., 1992). However, wells drilled in lowland areas near sea water of the Avon Estuary were rich in sodium chloride, a saltwater intrusion effect which must be taken into account.

The Blomidon Formation is primarily thin bedded siltstone, but includes a significant component of laterally extensive sandstone beds. Deposition of the sandstone, siltstone and mudstone occurred in sandflat, playa mudflat and minor lacustrine settings. There is an overall fining-upward trend for strata of the blomidon Formation. The sandstone beds focus groundwater flow into springs which emerge out of higher slopes beneath the basalts on the flanks of North Mountain. Much of this water may originate as flow through the fracture network in the overlying basalt. Otherwise much flow is obtained through the important joint fracture network. In the northern part of the valley, wells drilled for Wolfville targets may need to be drilled quite deep to penetrate beneath the thick cover of Blomidon. Waters tend to be rich in calcium sulfate, calcium bicarbonate, iron and manganese, with higher values of alkalinity, hardness, pH and total dissolved solids (Trescott, 1968). In addition, the Blomidon can act, regionally, as a thick sealing aquitard for the multiple aquifers of the Wolfville.

The thick basalt flows of the North Mountain Formation underlying North Mountain are characterized by columnar jointing, vesicular flow tops and abundant fracturing, each of which may provide significant transmissivity. Connectivity is a problem in many areas and most original porosity is filled with hydrothermal zeolite minerals. The North Mountain Formation thus also may perform the function of regional aquitard. The overlying Scots Bay Formation is too thin and discontinuous onshore to be of significance to groundwater resources in the Valley, but may be important elsewhere.

Points to Investigate

In general, the primary geological characteristics of the Fundy Group in the Fundy Rift are very encouraging for groundwater potential. Porosities and permeabilities are generally good, and water flows are generally satisfactory. Recharge from both sides of the Annapolis-Cornwallis

Valley is likely. Regional- and local-scale aquitards may improve artesian confinement pressures. Local faulting and fracturing may prove to be important in all units. Aquifer beds can be expected to be common throughout the Fundy Group of the Annapolis-Cornwallis Valley, occurring in sandstone bodies of fluvial, alluvial fan, aeolian and sandflat facies within the Wolfville and Blomidon formations. Trescott (1968) implied that the location of good aquifer bodies may be relatively unpredictable, but this is not necessarily so. The sandstones with the best aquifer quality should be the aeolian facies of the Wolfville, although this facies is most common near the footwall fault margin on the north side of the basin and at the top of the formation. Previous studies have not identified much of this facies in the Wolfville area, but further study may reveal its presence. Well sorted fluvial sandstones and alluvial fan conglomerates are ubiquitous and may be more predictable, geographically and in stratigraphic succession, than previously imagined. Certain stratigraphic intervals or areas may concentrate tongues of fan conglomerate or channel sandstone deposits with predictable paleoflow trends. In general, paleoflow dispersal was from the southern margin toward the north, in the Valley. Other intervals within the Wolfville or Blomidon may concentrate thin but continuous sandflat sandstones. Overall, both the Wolfville and Blomidon formations fine-upward individually, as well as collectively, and so the best aquifer potential may be in lower portions of the Fundy Group. Within those units, there are higher-order cycles which may concentrate aquifer potential at certain stratigraphic levels. Most importantly, the specific aspects of sedimentologic and stratigraphic characteristics in the Valley and their distribution are not well documented, and a step forward in this direction may lead to new concepts of aquifer geometry and location.

LIST OF FIGURES

REFERENCES

Arguden, A.T. and Rodolfo, K.T.
1986: Sedimentary facies and tectonic implications of lower Mesozoic alluvial fan conglomerates of the Newark Basin, northeastern United States. Sedimentary Geology, v. 51, p. 97-118.

Birney De Wet, C.C. and Hubert, J.F.
1989: The Scots Bay Formation, Nova Scotia, Canada, a Jurassic carbonate lake with silica-rich hydrothermal springs. Sedimentology, v. 36, p. 857-873.

Brown, D.E. and Grantham, R.G.
1992: Fundy Basin Rift Tectonics and Sedimentation. Geological Association of Canada, Field Trip Guidebook A-3, 61p.

Bujak, J.P. and Donohoe, H.V.
1980: Geological Highway Map of Nova Scotia. Atlantic Geoscience Society, Special Publication No. 1.

Crosby, D.G.
1962: Wolfville map-area, Nova Scotia (21H/1). Geological Survey of Canada, Memoir 325, 67p.

Greenough, J.D., Jones, L.M. and Mossman, D.J.
1989: Petrochemical and stratigraphic aspects of North Mountain basalt from the north shore of the Bay of Fundy, Nova Scotia, Canada. Canadian Journal of Earth Sciences, v. 26, p. 2710-2717.

Greenough, J.D.
1995: Mesozoic Rocks. *In* H. Williams (ed.), Geology of the Appalachian-Caledonian Orogen in Canada and Greenland, Geological Survey of Canada, Geology of Canada, no. 6, p. 567-600.

Hallam, A.
1990: The end-Triassic mass extinction event. *In* V.L. Sharpton and P.D. Ward (eds.), Global Catastrophes in Earth History; An Interdisciplinary Conference on Impacts, Volcanism and Mass Mortality, Geological Society of America, Special Paper 247, p. 577-583.

Hamblin, A.P. and Rust, B.R.
1989: Tectono-sedimentary analysis of alternate-polarity half-graben basin-fill successions: Late Devonian-Early Carboniferous Horton Group, Cape Breton Island, Nova Scotia. Basin Research, v. 2, p. 239-255.

Hay, W.W., Thompson, S., Pollard, D., Wilson, K.M. and Wold, C.N.
1992: Results of a climate model for Triassic Pangea. Zbl. Geol. Paleont, V. 1, p. 1253-1265.

Henigar, T.W., Gibb, J., Cruickshanks, F. And Rothfischer, J.
1992: Hydrogeological and groundwater interests in the Annapolis-Cornwallis Valley. Geological Association of Canada, Field Excursion Guidebook C-4, 15p.

Hodych, J.P. and Dunning, G.R.
1992: Did the Manicouagan impact trigger end-of-Triassic mass extinction? Geology, v. 20, p. 51-54.

Hubert, J.F. and Forlenza, M.F.
1988: Sedimentology of braided-river deposits in Upper Triassic Wolfville redbeds, southern shore of Cobequid Bay, Nova Scotia, Canada. *In* W. Manspeizer (ed.) Triassic-Jurassic Rifting, Elsevier, Amsterdam, p. 231-248.

Hubert, J.F. and Hyde, M.G.
1982: Sheet-flow deposits of graded beds and mudstones on an alluvial sandflat-playa system: Upper Triassic Blomidon redbeds, St. Mary's Bay, Nova Scotia. Sedimentology, v. 29, p. 457-474.

Hubert, J.F. and Mertz, K.A.
1980: Eolian dune field of Late Triassic age, Fundy Basin, Nova Scotia. Geology, v. 8, p. 516-519.

Hubert, J.F. and Mertz, K.A.
1984: Eolian sandstones in Upper Triassic-Lower Jurassic red beds of the Fundy Basin, Nova Scotia. Journal of Sedimentary Geology, v. 54, p. 798-810.

Jackson, C.T. and Alger, F.
1829: A description of the mineralogy and geology of a part of Nova Scotia. American Journal of Science, v. 15, p. 132-160.

Keppie, J.D.
1977: Plate tectonic interpretations of Paleozoic world maps (with emphasis on circum-Atlantic orogens and southern Nova Scotia). Nova Scotia Department of Mines and Energy, Paper 77-3.

Keppie, J.D.
1982: The Minas Geofracture. *In* Major Structural Zones and Faults of the Northern Appalachians, P. St-Julien and J. Béland (eds.), Geological Association of Canada, Special Paper 24, p. 263-280.

Klein, G. de V.
1962: Triassic sedimentation, Maritime Provinces, Canada. Geological Society of America Bulletin, v. 73, p. 1127-1145.

Klein, G. De V.
1963: Regional implications of Triassic paleocurrents, Maritime Provinces, Canada. Journal of Geology, v. 71, p. 801-808.

Kontak, D.J.
2001: Internal stratigraphy of the Jurassic North Mountain Basalt, southern Nova Scotia. Nova Scotia Department of Natural Resources, Minerals and energy Branch, Report of Activities 2001, p. 69-79.

Lorenz, J.C.
1988: Triassic-Jurassic Rift-Basin Sedimentology: History and Methods. Van Norstrand Reinhold Co., New York, 315p.

Manspeizer, W.
1981: Early Mesozoic basins of the central Atlantic passive margins. *In* A.W. Bally (ed.), Geology of Passive Continental Margins, American Association of Petroleum Geologists Education Course Notes 19, p. 1-60.

Manspeizer, W.
1988: Triassic-Jurassic rifting and opening of the Atlantic: an overview. *In* W. Manspeizer (ed.) Triassic-Jurassic Rifting, Elsevier, Amsterdam, p. 41-79.

Mertz, K.A. and Hubert, J.F.
1990: Cycles of sand-flat sandstone and playa-lacustrine mudstone in the Triassic-Jurassic Blomidon redbeds, Fundy rift basin, Nova Scotia: implications for tectonic and climatic controls. Canadian Journal of Earth Sciences, v. 27, p. 442-451.

Nadon, G.C. and Middleton, G.V.

1985: Tectonic control of Triassic sedimentation in southern New Brunswick: local and regional implications. Geology, v. 12, p. 619-622.

Olsen, P.E.
1988: Paleontology and paleoecology of the Newark Supergroup (early Mesozoic, eastern North America). *In* W. Manspeizer (ed.) Triassic-Jurassic Rifting, Elsevier, Amsterdam, p. 185-230.

Olsen, P.E.
1997: Stratigraphic record of the Early Mesozoic breakup of Pangea in the Laurasia-Gondwana rift system. Annual Review of Earth and Planetary Sciences, v. 25, p. 337-401.

Papezik, V.S., Greenough, J.D., Colwell, J.A. and Mallinson, T.J.
1988: North Mountain basalt from Digby, Nova Scotia: models for a fissure eruption from stratigraphy and petrochemistry. Canadian Journal of Earth Sciences, v. 25, p. 74-83.

Powers, S.
1916: The Acadian Triassic. Journal of Geology, v. 24, p. 1-26, 105-122, 254-268.

Sloss, L.L.
1988: Tectonic evolution of the craton in Phanerozoic time. *In* L.L. Sloss (ed.), Sedimentary Cover - North American Craton, US, Geological Society of America, The Geology of North America, v. D-2, p. 25-51.

Smitheringale, W.G.
1973: Geology of parts of Digby, Bridgetown and Gasperau Lake map-areas, Nova Scotia (21A/12, East Half; 21A/14, East Half; 21A/15, West Half). Geological Survey of Canada, Memoir 375, 78p.

Swift, D.J.P., Jagodits, F.L., Ministre, B.L. and Paterson, N.R.
1967: Structure of Minas Passage, Bay of Fundy: a preliminary report. Maritime Sediments, v. 3, p. 112-118.

Tanner, L.H.
1996: Formal definition of the Lower Jurassic McCoy Brook Formation, Fundy Rift Basin, eastern Canada. Atlantic Geology, v. 32, p. 127-135.

Tanner, L.H.
2000: Triassic-Jurassic lacustrine deposition in the Fundy rift Basin, Eastern Canada. *In* Lake Basins Through Space and Time, E.H. Gierlowski-Kordesch and K.R. Kelts (eds.), American association of Petroleum Geologists, Studies in Geology, v. 46, p. 159-166.

Tanner, L.H. and Hubert, J.F.
1992: Depositional facies, paleogeography and paleoclimatology of the Lower Jurassic McCoy Brook Formation, Fundy Rift basin, Nova Scotia. Paleogeography, Paleoclimatology, Paleoecology, v. 96, p. 261-280.

Tanner, L.H. and Brown, D.E.
1999: The Upper Triassic Chedabucto Formation, Guysborough County, Nova Scotia: depositional and tectonic context. Atlantic Geology, v. 35, p. 129-138.

Taylor, F.C.
1969: Geology of the Annapolis-St. Marys Bay map-area, Nova Scotia (21A, 21B East Half). Geological Survey of Canada, Memoir 358, 65p.

Trescott, P.C.
1968: Groundwater resources and hydrogeology of the Annapolis-Cornwallis Valley, Nova Scotia. Nova Scotia Department of Mines, Memoir 6, 159p.

Van Houten, F.B.

1964: Cyclic lacustrine sedimentation, Upper Triassic Lockatong Formation, central New Jersey and adjacent Pennsylvania. Bulletin of Kansas Geological Survey, v.169, p. 497-531.

Wade, J.A., Brown, D.E., Traverse, A. And Fensome, R.A.

1996: The Triassic-Jurassic Fundy Basin, eastern Canada: regional setting, stratigraphy and hydrocarbon potential. Atlantic Geology, v. 32, p.189-231.

Withjack, M.O., Olsen, P.E. and Schlische, R.W.

1995: Tectonic evolution of the Fundy rift basin, Canada: Evidence of extension and shortening during passive margin development. Tectonics, v. 14, p. 390-405.

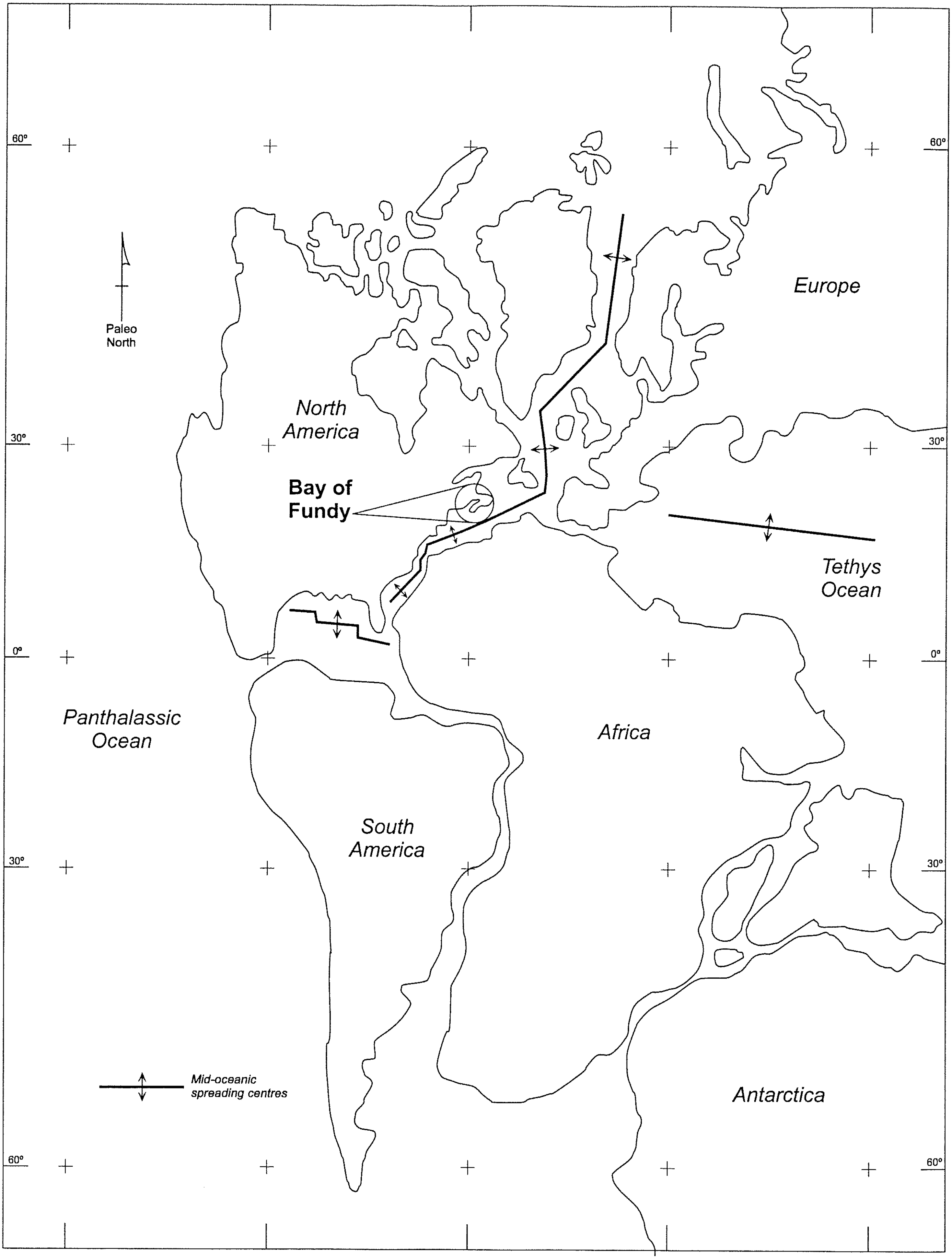

Figure 1. The beginnings of breakup of the Pangean Supercontinent ~ 220 ma. Middle Triassic (modified from Keppie, 1977).

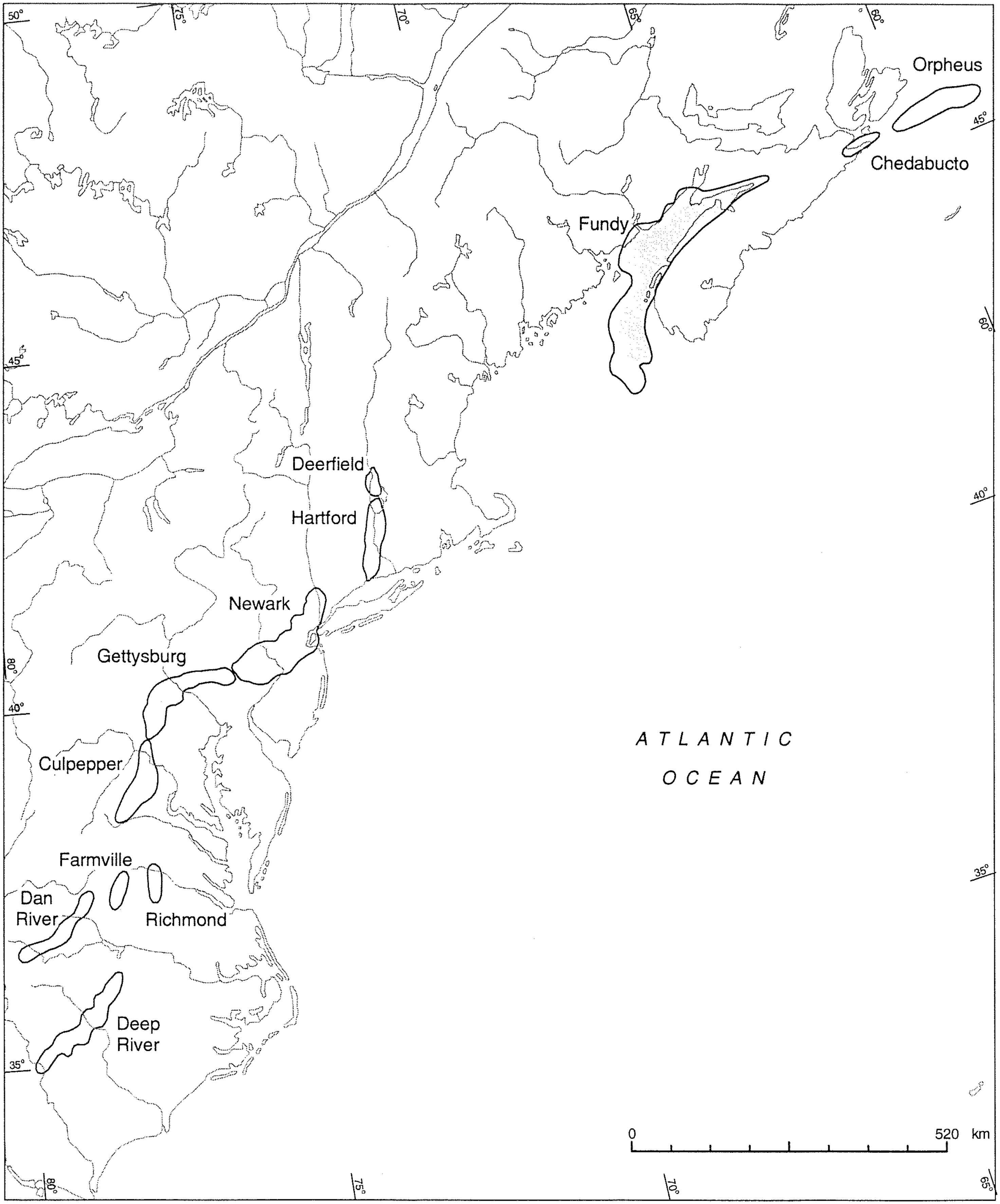

Figure 2. Newark Supergroup Basins (modified from Brown and Grantham, 1992).

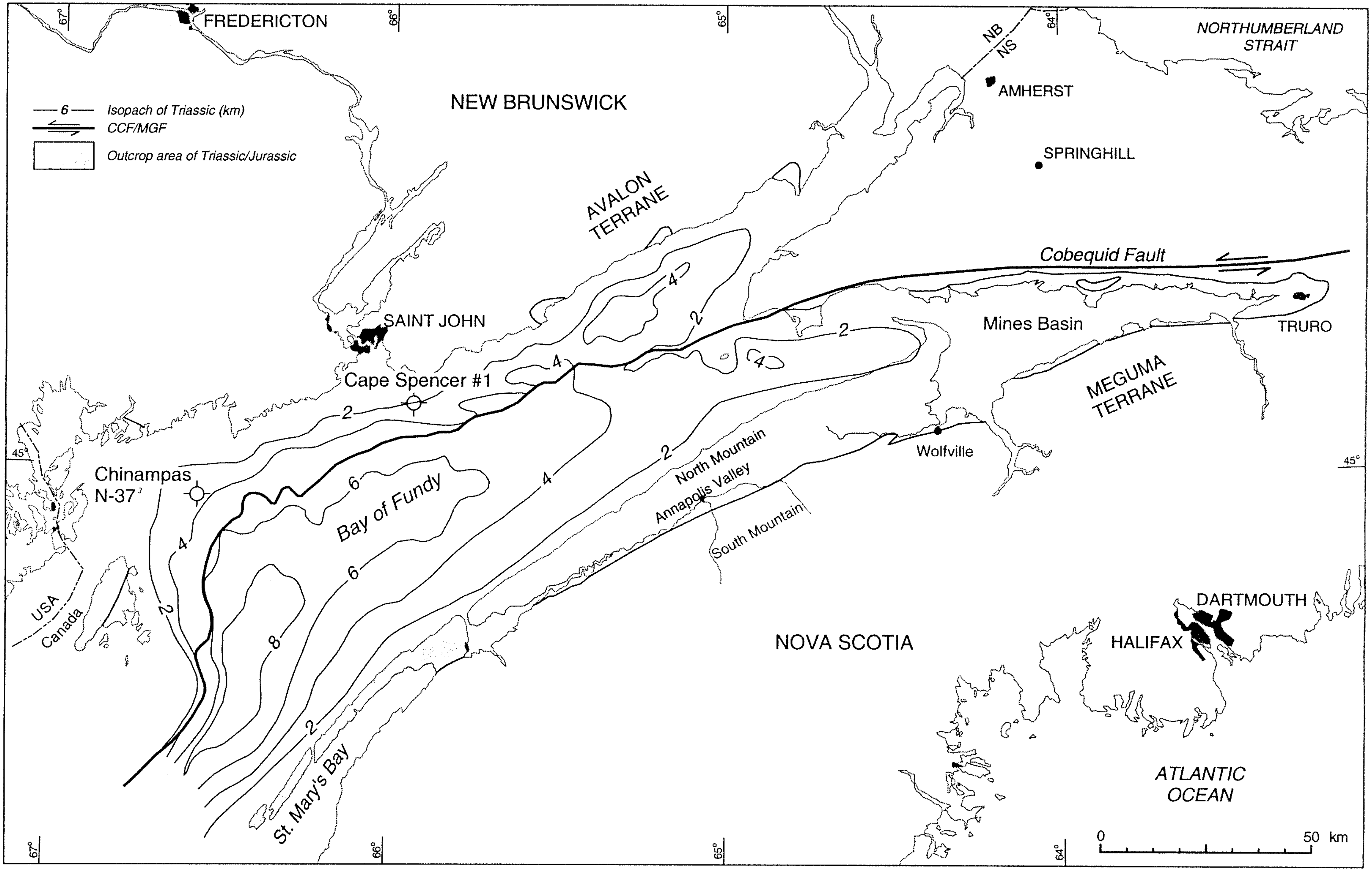

Figure 3. Isopach of Fundy Group rocks (modified from Wade et al., 1996).

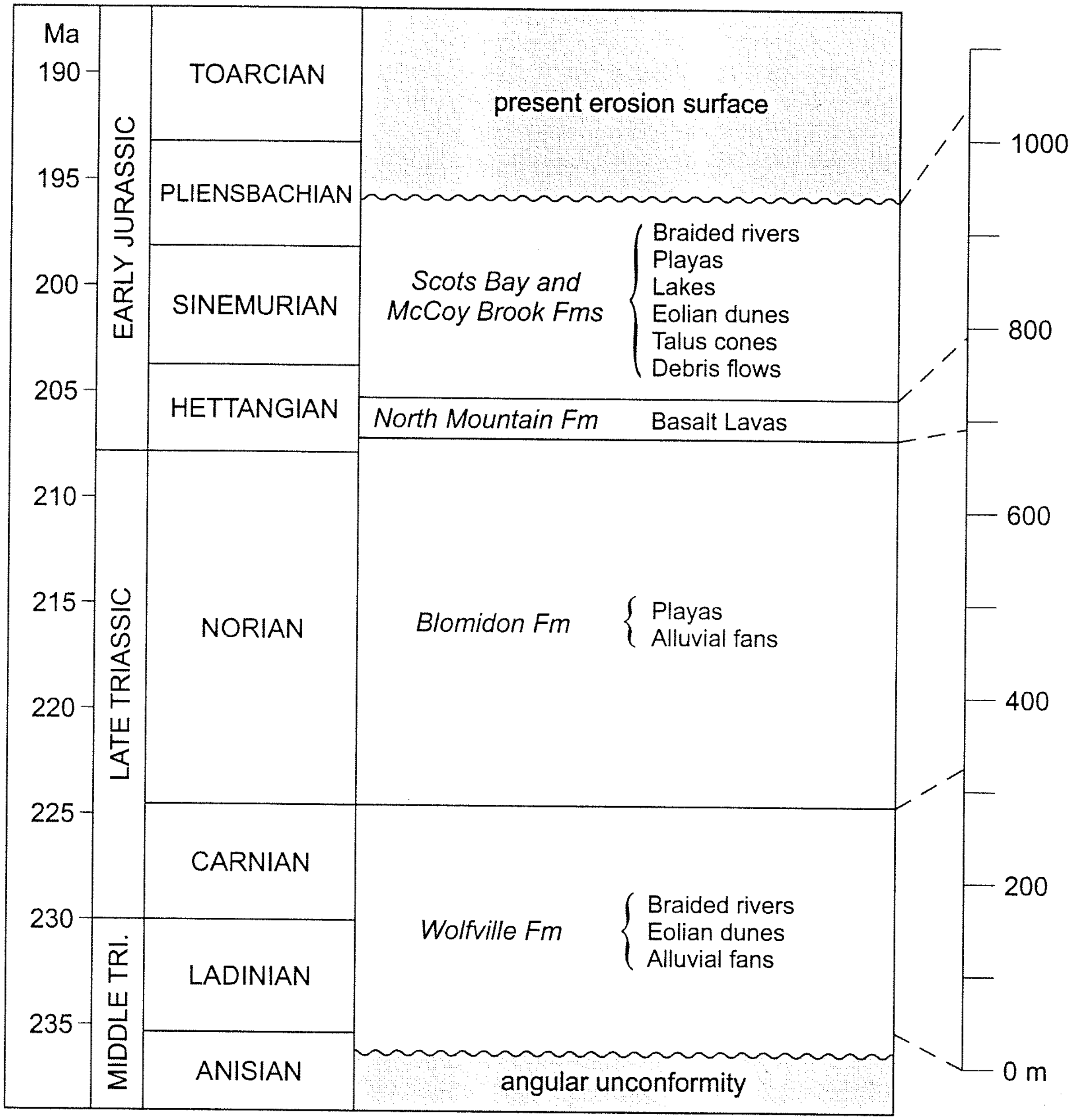

Figure 4. Stratigraphic relationships of Fundy Group sediments, Minas Sub-Basin (modified from D. Brown and Grantham, 1992).

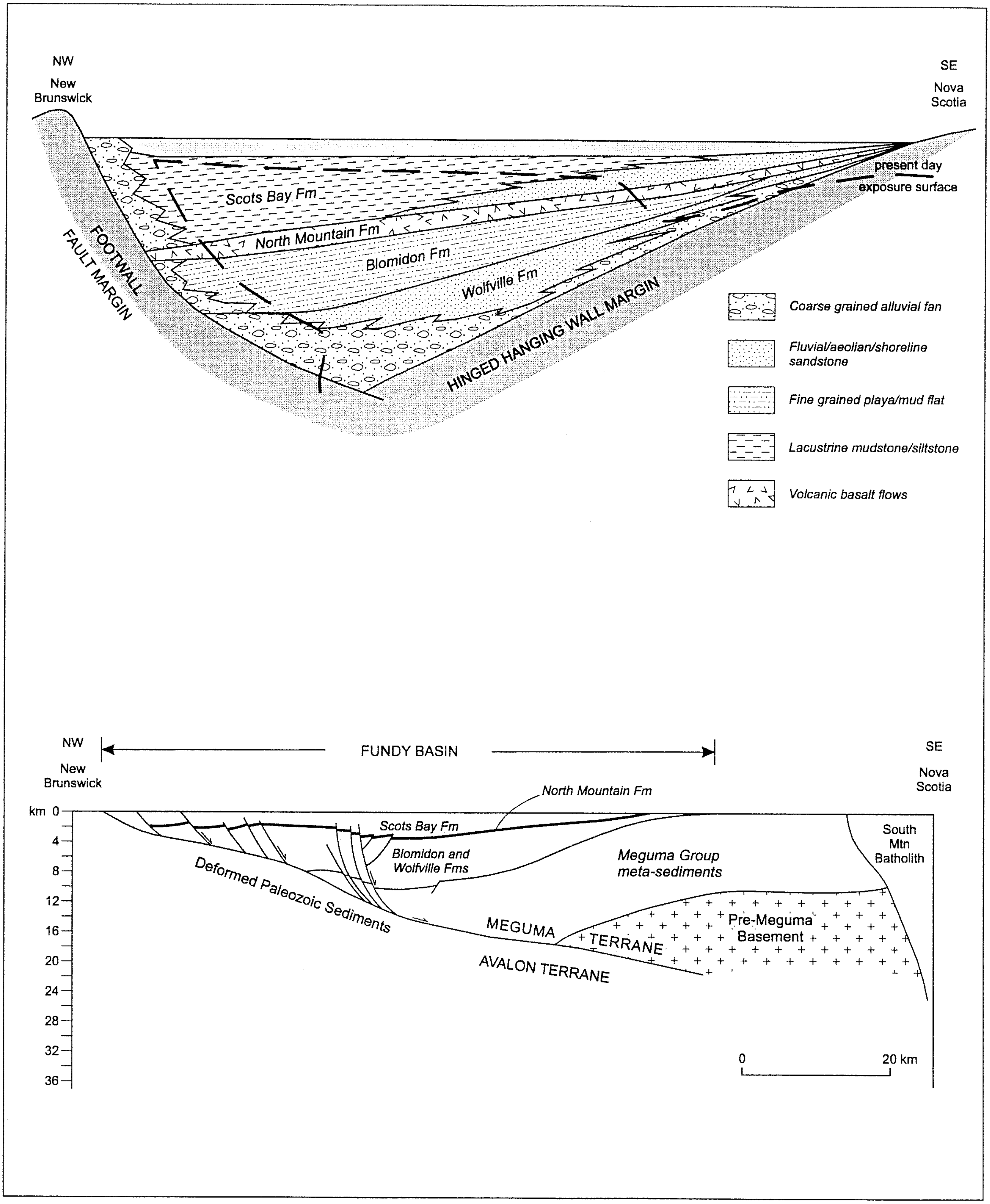

Figure 5. A) Simplified schematic depositional model and facies relationships for Fundy Basin. B) Present day structural configuration of Fundy Basin near mouth of Bay of Fundy (modified from Wade et al., 1996).

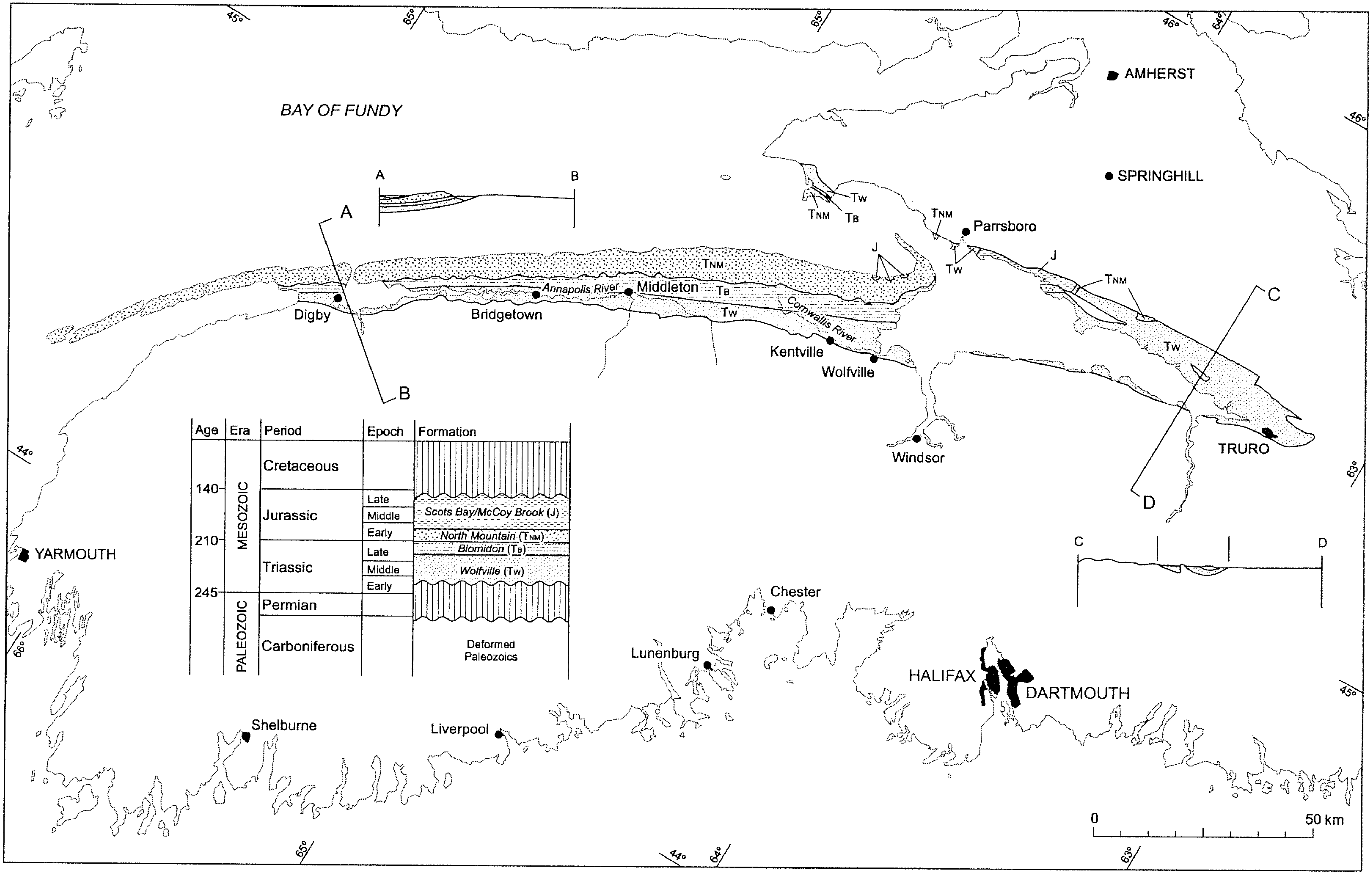

Figure 6. Triassic-Jurassic Rocks of the Annapolis - Cornwallis Valley (modified from Bujak and Donohoe, 1980).