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Chronology and stratigraphy of the Fundy and related Nova Scotia offshore basins and Morocco based on core and outcrop

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The Late Triassic age Blomidon Formation consists nearly entirely of massive gypsiferous mudstone and sandstones arranged into distinctive sand patch cycles, many of which show various salt dissolution features. Identical Late Triassic, cyclical, largely clastic facies are widespread in Morocco, on the conjugate margin to Nova Scotia, where Blomidon-like strata frequently pass in the subsurface into extensive thick and laterally extensive halite deposits. Similar deposits are also present on the Scotian, Newfoundland, and Moroccan shelves.

The GAV-77-3 core, collected by Getty Mines in 1977 as part of a Uranium prospecting survey, covers nearly all of the North Mountain Basalt and the entire fine-grained portion of the Blomidon Formation. Two other cores, GAV-77-1 and GAV-77-2, were also collected in the same area, but cover less of the section. These cores nicely complement the spectacular outcrops along the Fundy shores and provided a basis for the development of a complete lithological and paleomagnetic reversal stratigraphy for the Blomidon Formation (Kent and Olsen, 2000). The paleomagnetic polarity stratigraphy of the outcropping Blomidon Formation is known only for isolated intervals, but in conjunction with lithostratigraphy allow unambiguous correlation registry between core and outcrop. Correlation of the GAV-77-3 core polarity stratigraphy with the Newark GPTS, also based on core, is fairly straightforward as is correlation with the Moroccan Bigoudine Formation of the Argana basin.

These correlations demonstrate that the major cyclical wet climatic intervals in the Newark basin sequence can be recognized in the Fundy and Argana basins and should also be expressed in the intervening basins on the shelves. In addition they demonstrate the synchrony of major climate changes caused by the very long-term celestial mechanical cycles of a very large part of central Pangea.

Introduction

One of the most characteristic features of the rift basins of the central Atlantic margin (Fig. 1) is thick sequences of red mudstone of Late Triassic (and sometimes Early Jurassic) age. In the more northern basins of present day Maritime Canada, Morocco, Iberia, Central Europe and Great Britain, these red mudstones are often associated with evaporates, which sometimes

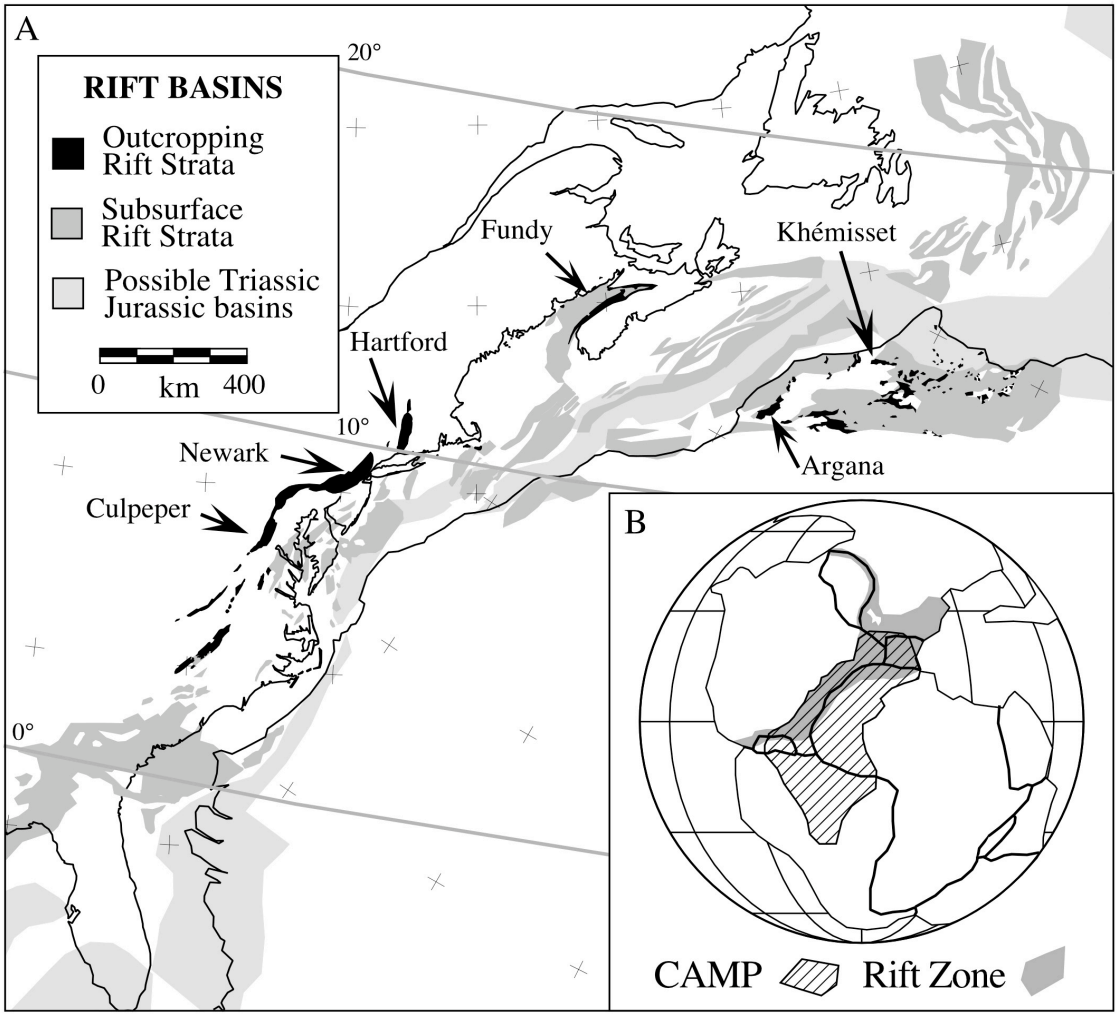

Figure 1: Distribution of central Atlantic margin rift basins of central Pangea and the distribution of the Central Atlantic Magmatic province (CAMP). A, Rift basins of the central Atlantic margins of North America and western Africa in predrift coordinates (for the Late Triassic) showing basins discussed in this paper; B, Pangea during the earliest Jurassic showing the distribution of the CAMP, overlapping much of the Triassic-Jurassic rift zone.

reach kilometers in thickness. Although these evaporates are often of critical importance to the petroleum system, their overall stratigraphic, climatic, and temporal context as well as that of the associated clastics are surprisingly poorly understood.

In this core workshop we will examine portions of the Getty Mines GAV-77-3 core, drilled in the Fundy rift basin (Figs. 2). GAV-77-3 continuously samples most of the Early Jurassic age North Mountain Basalt and virtually all of the Late Triassic and earliest Jurassic Blomidon Formation (Fig. 3), one of these prominent evaporite-bearing, red mudstone units. Cyclostratigraphic and magnetostratigraphic analyses of this core and correlative outcrops along the shores of the Bay of Fundy have provided considerable insight into the chronology of the Central Atlantic rift basins.

Tectonostratigraphic Sequences of the Fundy and Argana Basins

The Fundy Basin of the Maritime provinces of Canada (Fig. 2a) is a very large half graben complex, with its main bounding faults on the northwest and north. The Argana

basin of Morocco is a much smaller basin than the Fundy and it is a southeastern extension of the large Essaouria basin (Fig. 2b). The Fundy and Argana basins have remarkably similar stratigraphic sections that are divided into four tectonstratigraphic sequences that are at least locally separated by synrift unconformities, termed, from the bottom up, TS I – TS IV (Olsen, 1997) (Fig. 4).

TS I: The Honeycomb Point (and probably the Lepreau Formation) of New Brunswick and the Ikakern formations comprise TS I in the Fundy and Argana basins respectively (Fig.4) (Olsen, 1997). Descriptions of undoubted examples of the hammer-headed amphibian *Diplocaulus* and a pareiasaur from the Ikakern (Jalil, 1996), as well as our preliminary paleomagnetic data from the Honeycomb Point and Ikakern formations demonstrate a Late Permian age. The Honeycomb Point Formation is distinctive in having well developed eolian strata, while the Ikakern does not, owing probably to the more southerly location of the Ikakern in Late Permian geographic coordinates (Olsen et al., 2000).

While there is evidence of deposition of the Ikakern Formation in an extensional basin setting (Medina, 1991), no such evidence exists for the Honeycomb Point Formation. In fact, the latter is almost lithologically identical to the apparently coeval Cap aux Meules Formation (Brisbois, 1981; Tanczyk, 1988) of the non-rift Magdalen basin the Gulf of St. Lawrence, which seems to have been deposited as a very broad sheet. The Honeycomb Point Formation could just be an outlier of this sheet, fortuitously preserved within the Fundy Rift. TS I has never been penetrated in the subsurface in the Fundy basin.

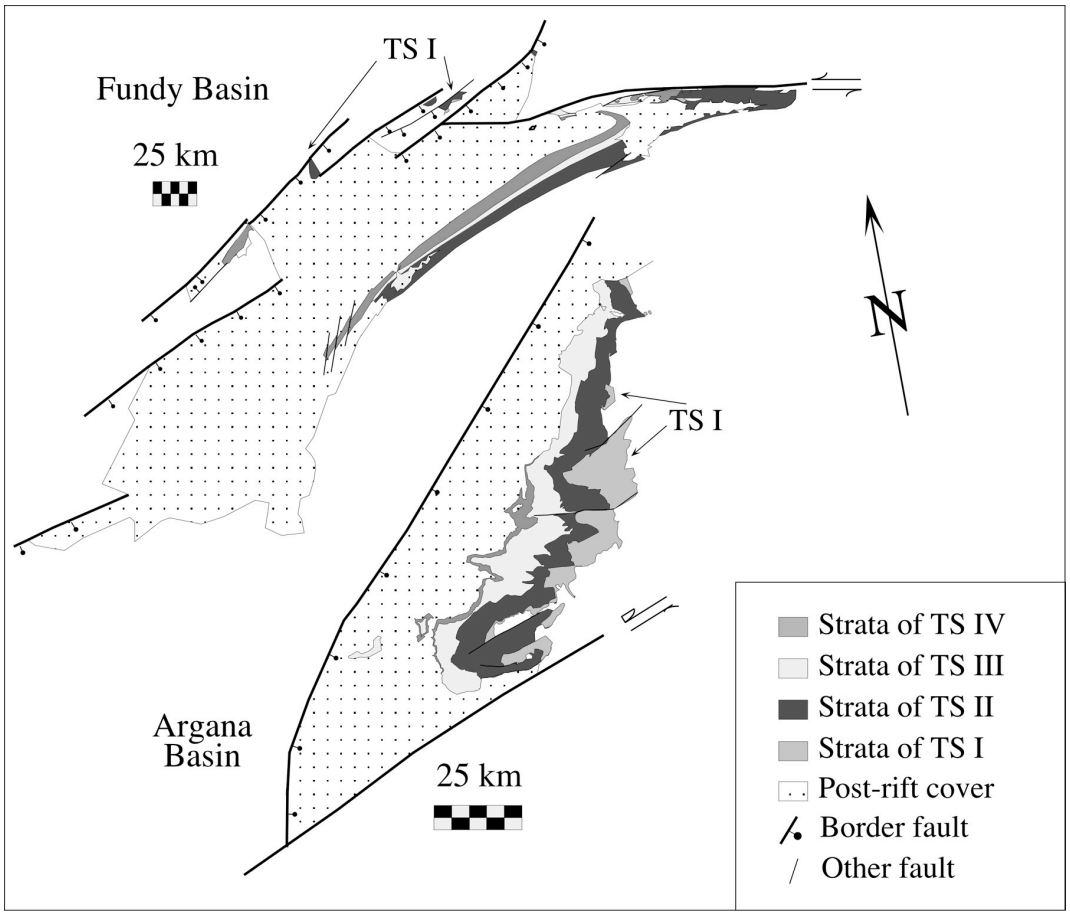

Figure 2: Fundy and Argana basins showing distribution of tectonostratigraphic sequences. From Olsen, 1977.

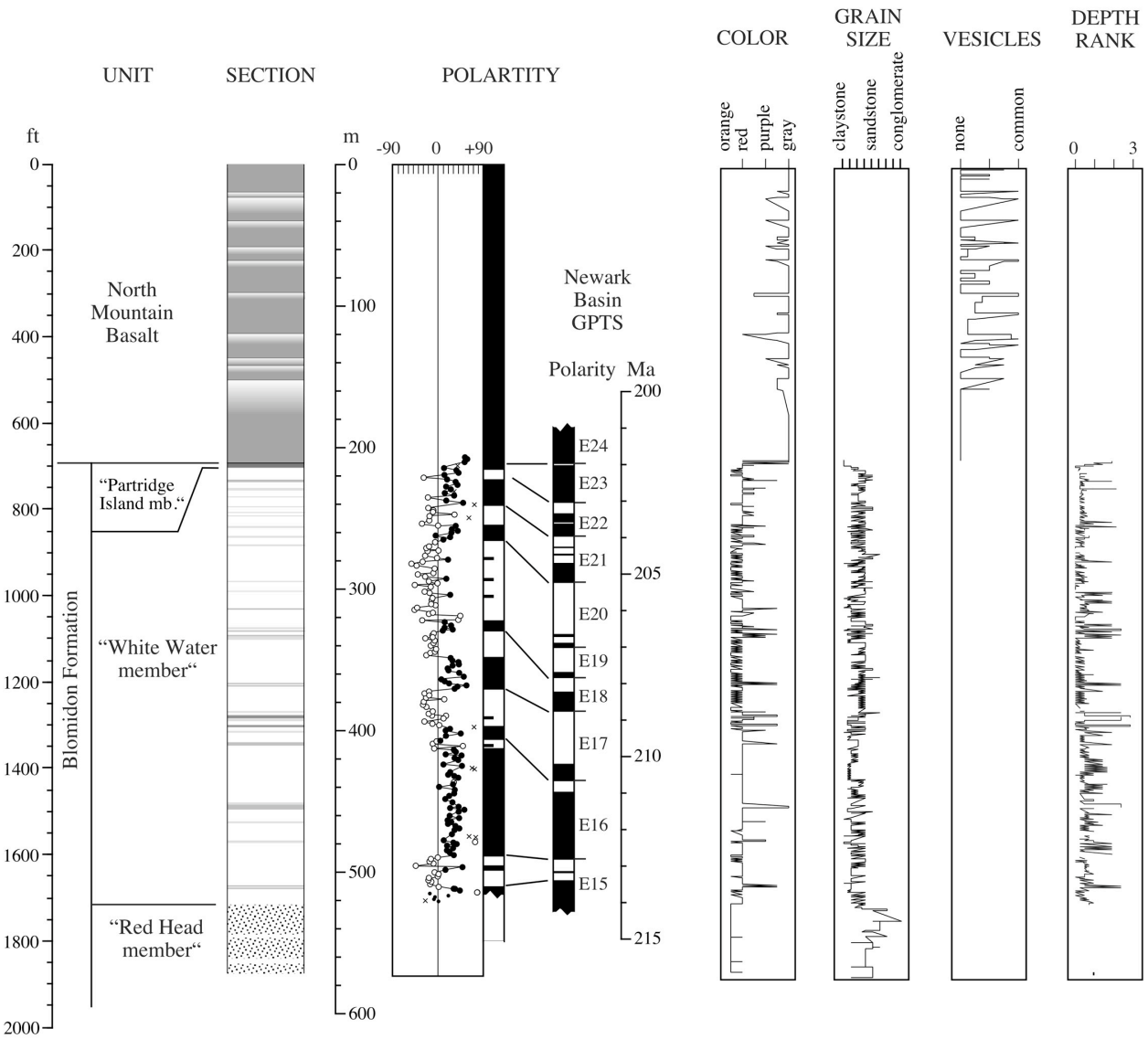

Figure 3: Getty Mines GAV-77-3 with the paleomagnetic polarity correlation to the Newark basin AGPTS (based on Kent and Olsen, 2000).

TS II: TS II overlies TS I unconformity in both the Fundy and Argana basins. The outcropping strata of TS II in the Fundy basin comprises the Wolfville Formation (revised, Fig. 4), which is mostly fluvial. However, subsurface data (Withjack et al., 1995) suggest that there are lacustrine equivalents to the Wolfville deeper within the basin as long suggested by Brown (in Wade et al., 1996) and are some seemingly cyclical lacustrine strata outcropping in the upper Wolfville Formation just north of Kingsport, Nova Scotia. In the Argana basin TS II consists of the Timesgadiwine Formation and consists of fluvial and lacustrine clastics with an especially well developed cyclical lacustrine sequence in the lower part of the Irohaline Member (T5) (Hofmann, et al., 2000) (Fig. 3). Based mostly on vertebrate remains augmented by some palynology, the age of TS II of the Fundy and Argana basins ranges from Middle to early Late Triassic age. TS II has also apparently not been sampled in the subsurface in the Fundy basin.

TS III: An angular unconformity at least locally separates TS II and TS III in the Argana and Fundy basins. In some areas, at least of the Fundy basin, a profound angular unconformity (~90°) separates the Wolfville Formation of TS II from the Blomidon Formation (redefined, Fig. 4) of TS III. In other areas there may be a gentle angular unconformity, or none at all, but existing outcrops do not permit resolution of this uncertainty. In the Argana basin, the upper Timesgadiwine Formation is truncated by a gentle angular unconformity (<5°: Fig. 4), at least locally (Tixeront, 1973; Olsen, 1997), and then overlain by the Bigoudine Formation of TS III. TS III is entirely of Late Triassic age. The GAV-77-3 core, the other GAV-77 cores, and the two deep Bay of Fundy drill holes, the Cape Spencer and Chinampas wells, bottomed in the lower part of TS III. Details of the stratigraphy of TS IV are given below in discussion of the GAV-77-3 core.

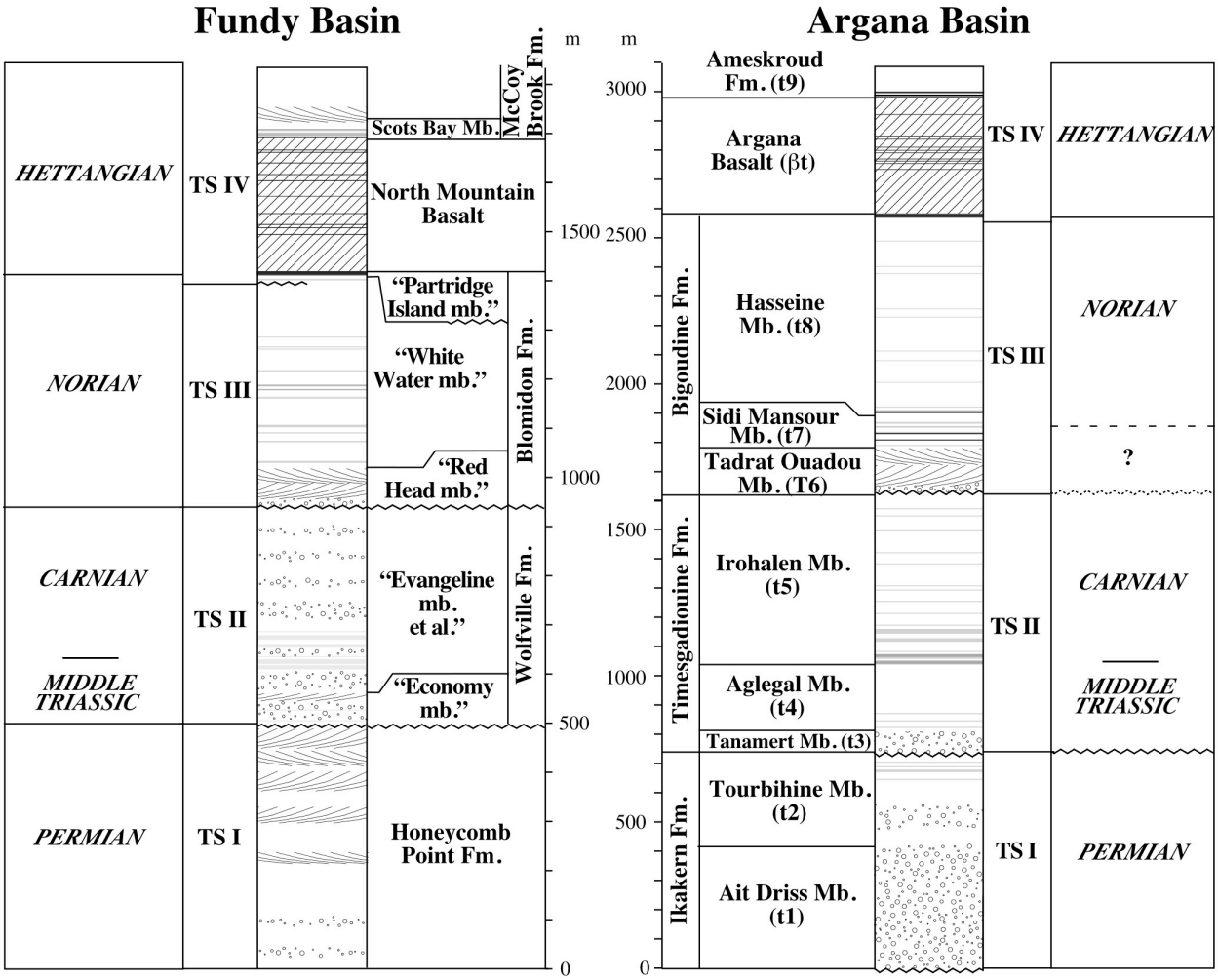

Figure 4: Tectonstratigraphy and age of the Argana and Fundy basins (modified from Olsen et al., 2000). Note that the members of the Fundy basin are presently informal units, with the exception of the Scots Bay Member (Tanner, 1996).

TS IV: TS IV of the Fundy basin consists of the uppermost portions of the Blomidon Formation, and successively overlying North Mountain Basalt and McCoy Brook Formations. The homotaxial sequence in the Argana basin is the Bigoudine formation, succeeded by the Argana basalt and an unnamed unit designated t9 (Fig. 4). The uppermost Bigoudine and Blomidon formations (upper “White Water” and "Partridge Island members") both begin with sand-patch-bearing red mudstones and sandstone, but within a few meters of the overlying basalts are a very distinctive suite of thin red, gray and black mudstone beds, which are generally palyniferous (barring local

metamorphism from the basalt) that contain the Triassic-Jurassic boundary (Fowell and Traverse, 1995; Olsen et al., 2002). We have informally, thus far, designated this extremely distinctive and mappable interval of the Blomidon Formation, the “Partridge Island member”.

The North Mountain Basalt and the Argana Basalt conformably overlie the uppermost Blomidon and Bigoudine formations in the Fundy and Argana basins, respectively (Fig. 2). Both basalt formations consists of two major flows and several thin interbedded and overlying flows which have, mostly high-titanium, quartz-normative type tholeiitic chemistry (see summary in Olsen et al., 2003). The North Mountain Basalt has yielded U-Pb ages of 202±1 Ma, in good agreement with other Eastern North American basalts (Hodych and Dunning, 1992). The Argana Basalt has not yet to be dated by more modern methods, but has produced a K/Ar date of 196±17 Ma (Manspeizer et al., 1978), with the large errors probably due to alteration. This age is consistent with the ages of the eastern North American basalts as well as similar basalts from Morocco (Olsen et al., 2003).

Overlying the basalt flow formations in both basins are thin carbonate-dominated units succeeded by predominately red clastic rocks. In the Fundy basin, the McCoy Brook Formation contains a basal carbonate-rich sequence of two white, green, purple, and red lake level cycles (Scots Bay Member) (De Wet and Hubert, 1989; Tanner, 1996) and overlying predominately red clastic rocks, including some very local eolian sandstones (Hubert and Mertz, 1984). These produce relatively rich vertebrate assemblages (Olsen et al., 1987) of Hettangian and possibly younger age (Lucas and Huber, 2000). In the Argana basin, t9 (Hofmann et al., 2000; Tourani et al., 2000), contains a basal carbonate and black shale sequence, followed by predominately red and brown mudstones and sandstones with a few thin gray beds. Likewise, TS IV has been encountered in the GAV-77-2 and GAV-77-3 cores, and in the Cape Spencer and Chinampas wells. Strata of TS IV are unconformably overlain by post-rift Quaternary strata in the Fundy basin and Early Jurassic conglomerates and marine strata in the Argana basin.

The GAV-77-3 Core

The Getty Mines GAV-77-3 drill core (Lat. 45°05’38”N, Lon. 64°58’35”W) was spudded on November 23, 1977 on North Mountain Basalt on the Nova Scotia shore of the Bay of Fundy (Fig. 5) along Kirk Brook at Morden, Kings County Nova Scotia. It was part of a Uranium prospecting program by Getty Minerals Company, Limited. Several other cores were collected, the longest being GAV-77-2 and GAV-77-1. A total of approximately 570 m of section was recovered in GAV-77-3, including ~208 m of North Mountain Basalt and ~362 m of the Blomidon Formation (Fig. 3). The core is entirely within TS III and TS IV. The 3.5 cm diameter (BQ) core is stored at Acadia University. The North Mountain basalt and Blomidon Formation were subjects of senior theses at Acadia (Adams, 1980 and Jong, 1985; respectively). Kent and Olsen (2000) presented the magnetic polarity stratigraphy of GAV-77-3, allowing detailed correlation to the Newark basin astronomically calibrated geomagnetic polarity time scale (AGPTS) (Fig. 3) (Kent and Olsen, 1999; Olsen and Kent, 1999). We will supply the original units (decimal feet) on the core when referring to specific beds.

North Mountain Basalt comprises the upper ~208 m of the core. Apparently, it was spudded in the lower part of the upper thick flow (17 m from its base) of the North Mountain basalt and then cut through at least 8 or 9 flows, 131 m thick in aggregate. Criteria for recognizing the flow boundaries consist largely of graded vesicle horizons at the tops of flows that are often reddened and glassy to very fine-grained chill margins.

Vesicle levels also occur within cooling units, however, and this introduces some uncertainty to the number of flows present. The lower thick flow is nearly 60 m thick.

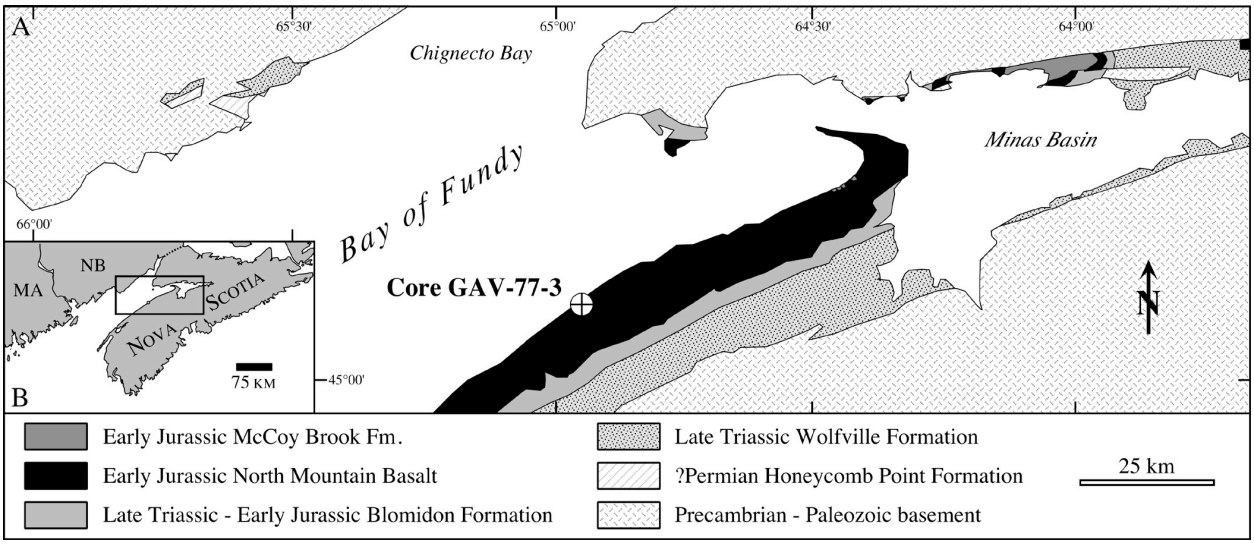

Figure 5: Location of Getty Mines GAV-77-3 (from Kent and Olsen, 2000).

The uppermost two meters of Blomidon Formation (see display) appears very similar to the nearly inaccessible outcrops at Cape Blomidon and at the easily reachable Partridge Island (Cumberland Co.). This interval is rather decimated by sampling in GAV-77-3 and is perhaps better seen in GAV-77-2. It contains a series of thin gray and black layers that are generally palyniferous, and on the basis of correlation to the Partridge Island section described by Fowell and Traverse (1995) the Triassic-Jurassic boundary is probably at 210.6 m (691.0 ft) in GAV-77-3 and at 171.1 m (561.4 ft) in GAV-77-2. This variegated unit was often though to be due of contact metamorphism, but of course metamorphism cannot make pollen and spores, although it can destroy them, as is frequently the case at many Blomidon-North Mountain Basalt contacts.

There is no obvious indication of an unconformity related to the TS III – TS IV boundary in the GAV-77-3 core. However, correlation of the core to the Newark basin AGPTS indicates that the accumulation rate was very much lower in the upper 10 m of the Blomidon than lower down. This could indicate the presence of a minor hiatus, but the available polarity data does not allow the position of a hiatus, should one exist, to be identified.

From 211.5 m (694.0 ft) to 523 m (1716.0 ft) the GAV-77-3 core consists of cyclical red gypsiferous mudstones and sandstones arranged largely in characteristic sequences termed sand-patch cycles (Smoot and Olsen, 1988; Olsen et al., 1989; Olsen, 1997; Tourani et al, 2000). This interval, informally designated by us the “White Water member” is typical of the Blomidon Formation and is identical in facies to the correlative Hasseine Member of the Bigoudine Formation of the Argana basin. A representative sequence of cycles are see in the interval from 369.3 m (1211.5 ft) to 387.9 m (1272.5 ft).

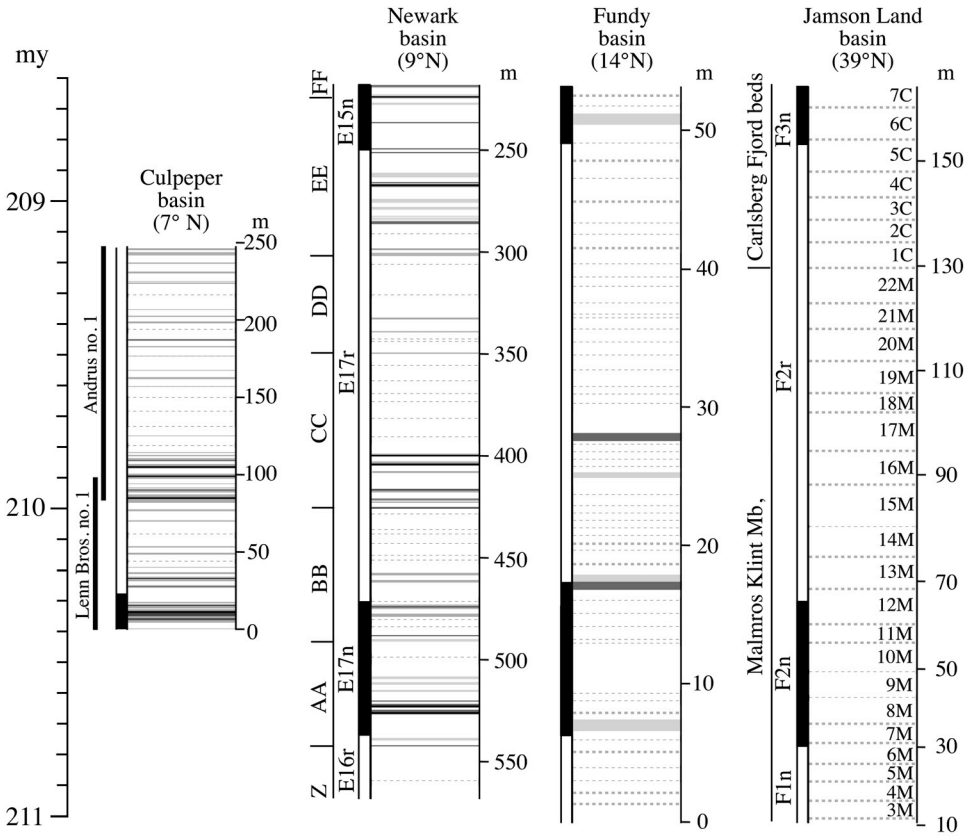

Figure 6: Comparisons of correlative sections of the Culpeper, Newark, Fundy, and Jameson Land basins. Culpeper section is from the Lenn Bros. no. 1 and Andrus no. 1 cores of the Bull Run Formation (Balls Bluff Siltstone), Newark section is from the Somerset no. 1 core of the middle Passaic Formation (E16r-E16n are magnetic polarity zones, and Z-FF are member names), Fundy basin section is based on outcrop (Blomidon area, Nova Scotia) correlated by lithostratigraphy to the GAV-77- 3 core which is the source of the magnetostratigraphy; Jameson Land basin section is based on Clemmensen et al. (1998) (3M-7C are Clemmensen's designations of ~100 Ky cycles). From Olsen and Kent (2000).

There are several intervals of laminated mudstone and dolomitic mudstone that do not fit well with the sand patch motif. Rather they tend to have laminated red, gray, and yellow dolomitic layers and are often associated with small to large-scale salt dissolution features. Two such layers are present at about 390.5 m (1281 ft) and 396.9 m (1302 ft). Dissolution features cannot be seen clearly in the cores, but are very well displayed in outcrops near Del Haven, King County, Nova Scotia and have been described by Ackerman et al. (1995). Although, we find the arguments presented by Ackerman et al. convincing, Tanner (2002) ascribes these same deformation features to a paleoseismic event associated with the impact that produced the Manicouagan impact structure. This interval apparently correlates to black shales in members BB and CC of the Newark basin (Olsen and Kent, 2000) (Fig. 6) which certainly indicates that the humid intervals in the two basins were coeval, but the dissolution features suggest a significant source of salt (halite) as well.

The first bed of pebbly sandstone occurs just below 523 m (1716.0 ft). From there to the base of the core, the section is dominated by sandstone and pebbly sandstone.

Traditionally, these coarse clastics have been grouped within the Wolfville Formation. This cored interval and its outcropping correlatives differ from the typical Wolfville in a number of respects, specifically in the low degree of bioturbation. especially by roots, and by the presence of eolian sandstones, that are occasionally spectacular. Hubert and Mertz (1984) described thick eolian dune sequences from Red Head in Five Islands provincial Park. At the east side of Red Head, these dune sequences are interbedded with laterally continuous mudstone and sandstone beds very similar to the overlying White Water member. At Pinnacle Island and at Lower Economy (Colchester Co.), these predominately sandstone and conglomerate sequences lie with profound unconformity upon Wolfville strata. Because these coarser grained strata pass upward into the White Water member and are at least locally separated from the underlying more typical Wolfville Formation by an unconformity we have informally designated the interval the "Red head member" of the Blomidon Formation and recognize it as the locally basal division of TS III. There is no indication that GAV-77-3 enters facies typical of the true Wolfville Formation (i.e., TS II). The base of the core appears to correlate with polarity zone E15 and member T-U of the Newark basin, which is one of the most arid looking intervals in the entire basin sequence.

It is apparent that the large-scale cyclicity of the Blomidon Formation broadly matches that of the correlative parts of the Newark basin. However, compared to the Newark basin, that cyclicity is distorted by both long and short-term accumulation rate fluctuations. We believe this is largely due to the very slow accumulation rate of the Blomidon Formation in outcrop and core.

Khémisset Basin

The Khémisset basin of Morocco (Fig. 7) appears to consist nearly entirely of TS III and TS IV (Fig. 4). In outcrop the stratigraphy of the basin section is strongly reminiscent of TS III and TS IV in the Fundy and Argana basins. Over most of the basin the basal formation is the Lower Clay formation, which looks virtually identical to the White Water member of the Blomidon Formation of the Fundy basin and the Hasseine Member of the Bigoudine Formation of the Argana basin. Similarly the uppermost Lower Clay formation as a 2 m thick palyniferous interval of red, gray, and black mudstone containing the Triassic-Jurassic boundary that resembles the Partridge Island member (Olsen et al., 2002). This is followed by a basalt flow sequence caped by a carbonate-rich interval. A major difference in the stratigraphy of this basin, compared to the Fundy and Argana basins, is that in many places another basalt flow sequence, chemically similar to the first, lies on top of the carbonate sequence. This second basalt unit is then overlain by strata similar to fine grained facies of the McCoy Brook Formation of the Fundy basin (Olsen et al., 2003), called the Upper Clay formation.

In the subsurface, however, the 2 m variegated unit resembling the Partridge Island member passes laterally into nearly 100 m of bedded salt (halite and potash salt), which is similarly variegated (Et-Touhami, 2000). Likewise the lower upper clay formation passes laterally into over 500 m of salt, cyclically interbedded with thin red mudstones, followed upwards by red gypsiferous mudstone.

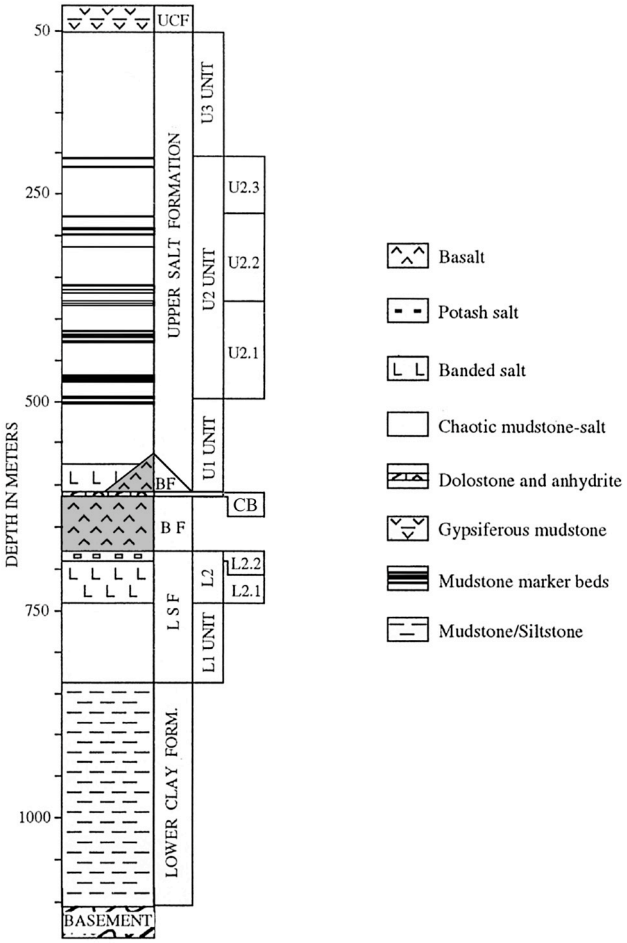

Figure 7: Stratigraphy of the central (and mostly subsurface) Khémisset basin, Morocco: CB, carbonate bed (Nif Gour beds); BF, Basalt formation (upper part not to scale); LSF, Lower Salt formation; UCF, Upper Clay formation. Modified from Et-Touhami (2000).

The subsurface stratigraphy of the Khémisset basin is clearly similar to not only several other subsurface basins of Morocco, but also subsurface sections on the Scotian and Newfoundland shelves (Holser et al., 1988; Pe-Piper et al., 1992). What is particularly interesting is that the Fundy basin outcrop and core sections resemble those of the Khémisset basin so closely. We suggest that the onset of thick salt deposition marks the initiation of TS IV, probably associated with a widespread extensional pulse reflected in the local creation of large-scale accommodation space (for the salt), eruption of the lavas, and regional subsidence that allowed the seepage of marine waters (already fractionated) into the basin (c.f., Olsen et al, 2003; Schlische et al., 2003).

Conclusions

The similarities between the stratigraphy of the Fundy, Argana, and Khémisset basins and the offshore basins, along with correlation to the Newark AGPTS argue that the facies typical of TS III and IV in the Fundy basin are the clastic equivalents of much of the Osprey and Argo salts in offshore Maritime Canada. In addition, the onset of thick evaporite deposition as well as the extrusion of the basalt flows in onshore Moroccan

basins, such as the Khémisset, offshore Moroccan and Maritime Canadian basins was the result of the extensional pulse that produced tectonostratigraphic sequence TS IV.

In addition, the magnetostraigraphic correlations between the Fundy and Newark basin AGPTS show that the larger scale lacustrine cyclicity can be correlated between basins suggesting that similar high resolution correlations should be possible in the conjugate Maritime and Moroccan margins.

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