Constraints on syn-rift intrabasinal horst development from alluvial-fan and aeolian deposits (Triassic, Fundy Basin, Nova Scotia).

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ABSTRACT (< 200 WORDS)

The Triassic Fundy rift basin was a large (>70 km wide) half-graben filled with alluvial, lacustrine and aeolian deposits. A major lithospheric lineament, the Cobequid-Chedabucto Fault Zone (CCFZ) which forms the tip of the Newfoundland-Gibraltar Fault Zone, occurs within the Fundy Basin. The timing of early movement on this important fault zone is poorly constrained. Here we present data from the alluvial and aeolian units that crop out adjacent to the CCFZ in the Minas sub-basin to determine the initiation of fault movement. We use the onset of alluvial-fan deposition to infer when the fault became sufficiently active to create intrabasinal topography and document the influence of fault activity on intrabasinal drainage. The occurrence and preservation of aeolian deposits immediately adjacent to the CCFZ and concomitant with alluvial-fan development suggests a wind-shadow effect associated with fault-generated topography. The onset of alluvial-fan deposition associated directly with the fault occurred during Norian times, following an earlier phase of sedimentation in the Fundy Basin, and records a potentially important phase of plate reorganisation during early Atlantic rifting.

Triassic basin-fill successions present along the North American Seaboard have been the focus for studies of continental stratigraphy (e.g Cornet, 1977; Olsen et al., 1982; Olsen and Sues, 1986; Olsen et al., 1989; Fowell and Traverse, 1995; Whiteside et al., 2007; Lucas and Tanner, 2007; Cirilli et al., 2009), sedimentary evolution of rift basins (Smoot, 1991; Schlische and Olsen, 1990; Olsen, 1997; Leleu & Hartley 2010) and structural development of rift basins (e.g. Olsen and Schlische, 1990; Schlische, 1993; Withjack et al., 1995, 1998; Olsen, 1997). One of the key studied basins is the Fundy Basin due to excellent exposure and a subsurface database (Olsen and Schlische, 1990; Schlische, 1993; Wade et al., 1996; Withjack et al., 1995, 1998). Recent studies have considered sediment distribution at a basin scale in the Fundy Basin in relation to the tectonic framework (Leleu & Hartley, 2010; Leleu et al., 2009, 2010). Most previous studies have considered the present-day geomorphology of the Fundy Basin to be largely inherited from Triassic times as palaeogeographic models for the Late Triassic are basically based on present-day relief (e.g. Hubert & Mertz, 1984; Hubert & Forlenza, 1988). Late Triassic palaeogeographical representations consider the major fault zone in the centre of the Fundy Basin, the Cobequid-Chedabucto Fault Zone (CCFZ), to be a permanent feature during sedimentation with fluvial drainage networks derived from the uplifted fault block and draining southwards into the basin (Hubert & Mertz, 1984; Hubert & Forlenza, 1988). To assess the validity of these models and to constrain the timing of movement on this important fault system we examine the sedimentary succession exposed immediately adjacent to it. Thus recognition of alluvial-fan deposits and their integration within a stratigraphic context is crucial to evaluate the history of fault activity. The CCFZ links with the Newfoundland-Gibraltar Fault Zone and the timing of movement could yield important information regarding the onset of Atlantic rifting. At a more local scale, understanding drainage development within the basin allows the reconstruction of uplift history of the horst structure and how it modified drainage and sediment distribution. This paper highlights the problem of identifying structural and sedimentary linkages between different sub-basins in rift systems and aims to constrain the timing of fault movement using the development of alluvial-fan sedimentation adjacent to the CCFZ.

GEOLOGICAL SETTING

The Fundy Basin forms one of a series of NE-trending early Mesozoic rift basins developed along the Atlantic North-American margin following the trend of Caledonian structures (e.g. Manspeizer, 1988). It contains 6 to 12 km of Anisian to basal Hettangian non-marine clastic sediments in its depocenter (Olsen et al., 1989; Fowell and Traverse, 1995; Wade et al., 1996; **Figs. 1, 2**). The present-day basin is approximately 200 km in length and 70 km in width, and is divided into three structurally distinct sub-basins: the Minas, Chignecto and Fundy sub-basins, assumed to form a complex half-graben system (Wade et al., 1996; **Fig. 1A, B, C**). The Minas sub-basin is one of the rare E-W trending basins present along the North American margin and its orientation is probably related to the structural control imparted by the Caledonian Cobequid-Chedabucto Fault Zone (Schlische, 1993). This fault zone was reactivated with a strike-slip component during the latest Triassic and earliest Jurassic (Olsen and Schlische, 1990; Withjack et al., 1995). The Triassic succession in the Minas sub-basin forms a broad syncline that was subsequently inverted (**Fig. 1D**; Withjack et al, 1995) due to movement on the CCFZ which resulted in faulting and fragmentation of the northern edge of the Minas sub-basin such that the overall Triassic depositional geometry on the northern basin margin is difficult to constrain (Withjack et al. 2009). The CCFZ itself is a complex fault zone with 2 major faults trending E-W and many smaller scale faults, some of which trend NE-SW (Olsen & Schlische 1990; **Fig. 1A, 3**).

Structural background

Published cross-sections based on seismic surveys are available and provide a structural framework for the basin (e.g. Schlische, 1993; Wade et al., 1996; Withjack et al., 2010). The Fundy Basin border fault corresponds to a re-activated low-angle Caledonian thrust fault that trends NE-SW (Schlische, 1993; Withjack et al., 1995). The border faults are the Chignecto Fault in the Chignecto sub-basin and the Headlands Fault running along the New Brunswick coastline in the Fundy sub-basin. The interpreted seismic profile (**Fig. 1A, B, C**) shows the development of a sedimentary wedge thickening towards the border faults.

The present-day Minas sub-basin is defined to the south by the contact of Triassic sediments and the southern granitic uplands, and to the north by the CCFZ. There are limited structural data for the Minas sub-basin with only one recent study illustrating one N-S section (**Fig. 1D**) and one NE-SW section in the western part

(**Fig.1B**; Withjack et al., 2010), but the relationships between stratigraphic units and faults are not obvious on these sections. A seismic profile through the western part of the Minas sub-basin and one through the Fundy sub-basin (**Fig. 1B, C**) show that Triassic sediments thicken towards the CCFZ, suggesting that the fault was active during deposition. Detailed field studies along the northern Minas coast show that strike-slip motion occurred along the CCFZ during earliest Jurassic times (Olsen & Schlische, 1990; Withjack et al., 2009; 2010). Olsen & Schlische (1990) recorded complex fault patterns interpreted as part of a larger scale left-oblique slip along the fault system during early Mesozoic extension (**Fig. 3**). Despite the complex outcrop pattern, the sedimentary succession close to the CCFZ can be reconstructed and applied to constrain the development of the northern margin of the Minas sub-basin during the Late Triassic. The studied sections are highly faulted and located three to five kilometres south of the main inland fault.

Stratigraphy of the Fundy Basin

Two main sedimentary packages fill the Fundy Basin and are recognized in seismic lines. The lower coarser unit is referred to as the Wolfville Formation and the upper finer unit is the Blomidon Formation (**Fig. 2**). The North Mountain Basalt conformably overlies the Blomidon Formation and is part of the Central Atlantic Magmatic Province (CAMP). These units are best exposed in the Minas sub-basin where they are dated as Late Triassic (Carnian to Rhaetian). The main volcanic phase of CAMP development is Rhaetian in age (e.g. Cirilli et al., 2009). The succession in the Chignecto sub-basin is not easily related to the units imaged offshore, most of which are considered older in age and likely represent the lowermost Triassic deposits present in the basin (Olsen et al., 2000; Leleu & Hartley, 2010). The Chignecto sub-basin comprises a 1600 m thick Triassic fluvial succession (the Quaco Formation and the overlying Echo Cove Formation) that rests unconformably on Permian strata (Nadon and Middleton, 1985; Olsen et al., 2000). The Quaco Formation consists of conglomerates interpreted to be the product of a large fluvial system flowing northwards (Klein, 1962; Nadon and Middleton, 1985). The Echo Cove Formation includes slope deposits and fluvial sediments that show palaeoflows towards the east-southeast and suggesting that sedimentation occurred on a fan (Nadon and Middleton, 1985). The oldest sediments were considered to be middle to late Carnian but could be Ladinian in age (Nadon and Middleton, 1985).

Stratigraphy of the Minas sub-basin

The Wolfville Formation lies unconformably on significantly older rocks and forms the main syn-rift unit in the Minas sub-basin (Wade et al., 1996). The Wolfville Formation is Carnian in age but an older, Anisian age, is hypothesised for one faulted outcrop along the northern shore (Olsen & Sues, 1986), known as the Carrs Brook section (**Fig. 3A**) and along the CCFZ. These deposits are older than the Wolfville Fm and represent a previous phase of rift development (Leleu & Hartley, 2010). Parts of the Echo Cove Formation in the Chignecto sub-basin are probably contemporaneous with some of the Carnian Wolfville Formation.

Based on facies and sedimentary architecture, the Wolfville Formation has been sub-divided into 3 informal units (**Fig. 4A-C**): the deposits of the lower and middle Wolfville Formation are interpreted as lateral distributive fluvial input to the basin, flowing to the north and sourced from the southern rift shoulder (Leleu et al., 2009, 2010; Leleu & Hartley, 2010). The lower Wolfville Formation corresponds to conglomeratic sediments deposited by alluvial fans and highly mobile fluvial channels (Leleu et al., 2009). The middle Wolfville Formation comprises sandy channel complexes and overbank deposits that represent the downstream facies equivalent of the underlying conglomeratic system (Leleu et al., 2010). The upper Wolfville Formation is interpreted as deposits of distal and smaller distributive fluvial systems, comprising splays and subordinate channel deposits alternating with aeolian and ephemeral-lacustrine sediments (Leleu & Hartley, 2010). These were deposited around 24/25° N (respectively Kent and Tauxe, 2005 and Van Houten, 1977) under semi-arid to sub-humid conditions (Tanner, 1993).

The Blomidon Formation overlies the Wolfville Formation (Olsen et al., 1989) and records a significant change in facies architecture comprising mainly laminated lacustrine mudstones, massive playa mudstones with occasional evaporites and patches of rippled sand within claystones, known as sandpatch fabrics (Hubert and Hyde, 1982; Mertz and Hubert, 1990; Smoot, 1990; Ackermann et al., 1995; Tanner, 2000; Leleu & Hartley, 2010; **Fig. 4D**). In the southern part of the basin it comprises sandy sheetflood deposits while finer-grained lacustrine sediments dominate in the northern area in proximity of the CCFZ (Gould, 2001).

SEDIMENTOLOGY OF THE LOWER ECONOMY DEPOSITS

The sediments of the Minas sub-basin studied along the CCFZ are located in three main sections around the locality of Lower Economy (**Fig. 3B**): the Economy Point Section, the Soley Cove Section and its lateral "equivalent" ending at the Red Head Section of Five Islands, studied previously by Hubert & Mertz (1980, 1984). This contribution describes the first two sections in detail and their relationship to the Red Head section. In the studied sections 11 lithofacies are recognised and described in **Table 1**, grouped into 4 facies associations based on lithofacies and sedimentary architecture.

The **Alluvial-Fan** facies association comprises mainly clast-supported breccia (*lithofacies 1*), matrix-supported breccia (*lithofacies 2*) and pebbly sandstones (*lithofacies 3*) (**Figs. 5A-E**). Breccias (*lithofacies 1 and 2*) record debris-flow and hyperconcentrated-flow deposition on alluvial fans while pebbly sandstones (*lithofacies 3*) indicate more fluidal streamflow events (**Table 1**). The granule-bearing sandstones and isolated sandsheet lithofacies (*lithofacies 4 and 6*) represent more distal fan-toe sediments (**Figs. 5F, G, H**) and are intercalated with playa-margin facies (**Fig. 6**). The isolated sandsheet (*lithofacies 6*) may have been deposited during the waning phase of flows which deposited the granule-bearing sandstone on the distal fan. The angular nature of the clasts, the occurrence of outsized clast sizes (up to 1m), the locally derived lithologies of the clasts (mainly gneiss and Carboniferous metasediments forming the present-day Cobequid High) and interpreted sedimentary processes suggest that deposition on the alluvial fans was very close to the sediment source and probably less than 8 to 10 km in length (e.g. Blair and McPherson, 1994).

The **Playa-Margin** facies association comprises mainly ripple-laminated sandstones (*lithofacies 8*), sand-patch sandstones (*lithofacies 5*) and claystones (*lithofacies 11*) (**Figs. 5I-M**), intercalated with granule-bearing sandstone (*lithofacies 4*) and locally with isolated sandsheets (*lithofacies 6*). The ripple-laminated sandstones (*lithofacies 8*) represent distal sheetflood deposits (**Fig. 5K**), downstream equivalents to coarser hyperconcentrated flows that left coarse sediments upstream on the fan surface (**Table 1**). They are intercalated with granule-bearing sandstones (*lithofacies 4*) that correspond to coarser sheetflood deposits that flowed further downstream on the fan surface. The ripple-laminated sandstones are typical deposits of the fan toe and are intercalated with the playa claystones (**Fig. 6**). Claystones (millimetric to centimetric horizons) drape ripples on top of the sheetflood deposits (*lithofacies 8*; **Fig. 5L**), and were likely deposited during waning flow phase, whilst thicker units most likely accumulated in ephemeral ponds. Some interference ripples (**Fig. 5M**) attest to the shallowness of the lake as wind-generated ripples reworked previous current ripples. Sand-patch fabric sandstones (*lithofacies 5;* **Table 1; Figs. 5I, J**) also suggest low lake levels and some periodic exposure, with the wind blowing across the wet playa surface generating "adhesion ripples". Soft sediment deformation of the ripples (**Fig. 5I**) is considered to be due to either evaporite dissolution initially present on or just below the playa surface, or to bioturbation (**Table 1**). The association of sand-patch sandstones (*lithofacies 5*) with ripple-laminated sandstones (*lithofacies 8*) and claystones (*lithofacies 11*) is typical of the Blomidon Formation assigned to middle to late Norian and Rhaetian (Fowell and Traverse, 1995).

The **Fluvial** facies association comprises cross-stratified sandstones (*lithofacies 7*), siltstones (*lithofacies 9*) and heterolithic deposits (*lithofacies 10*). It forms the Economy Point section that is over 30 metres thick of which only the basal 23 metres are accessible for detailed description (**Fig. 7**). The association represents a highly mobile fluvial system composed of large, amalgamated, multi-storey channel belts intercalated with relatively thick units of overbank deposits (over 12 metres in thickness for some intervals). The fluvial channel belts are wider than the outcrop length (> 4 km) and represent the amalgamation of migrating or avulsing channels. Intervals of floodplain deposits are not very well exposed but comprise thin intercalated claystones and sandstone beds that often show ripple cross-lamination (heterolithic deposits, *lithofacies 10*). These deposits form either foresets composed of intercalated claystones and sandstones that prograde over few meters and are interpreted as crevasse-splay deposits (**Table 1**, **Fig. 5N)** or comprise lenses of sandstones overlying small-scale shallow erosional features in fine-grained floodplain deposits, interpreted as crevasse-channel deposits.

The **Aeolian** facies association comprises quartzitic sandstones that were described in detail by Hubert & Mertz (1980, 1984). They consist of rounded to subrounded quartz grains that are moderately to very well sorted. The sandstones show preserved sets of large foresets up to 3.50 metres thick. Beds show either sub-horizontal stratification or steep cross-beds. The latter comprise grainflow deposits that are preserved on dune foresets and finer-grained well sorted grainfall deposits (Hubert & Mertz, 1980). Some cross-beds are tangential and show pin-striped laminae representing aggradation during wind-ripple migration. Similar wind ripples are present in the planar low-angle units and represent dune-toe deposits (Hubert & Mertz, 1984). Large-scale erosion surfaces were recognised for over 300 meters laterally and truncate smaller scale aeolian structures; they are horizontal with a few centimeters of erosional relief (Hubert & Mertz, 1980), and are interpreted as first-order bounding surfaces representing dry interdune development between events of dune accumulation (e.g. Brookfield 1977). Similar surfaces are often overlain by ventifact pebbles generally 2 to 4 cm in length, but locally pebble lags with pebbles up to 10 cm may be developed. Locally the quartzitic sandstones (Aeolian facies association) are interbedded with beds of pebbly sheetflood deposits (**Figs. 5O, 8**). The latter correspond to the breccia and pebbly sandstones (Alluvial Fan facies association) described above (see **Table 1**). These surfaces with pebble lags and occasionally overlain by alluvial deposits represent a significant hiatus in the aeolian record during which waterlain processes eroded part of the aeolian dune field and may represent super-surfaces (*sensu* Kocurek 1988). The aeolian deposits measured in the section at Red Head of Five Island represent the thickest aeolian section and most abundant Triassic aeolian dune deposits of the Minas sub-basin. Hubert and Mertz (1984) measured palaeoflow directions on aeolian dune foresets (n = 73) from the Red Head section with a mean palaeowind direction towards N254º.

SEDIMENTARY ARCHITECTURE ALONG THE COBEQUID FAULT

Economy Point section

At Economy Point (**Fig. 3**), laterally extensive outcrops (over 3 kilometres) of fine-grained fluvial deposits show channel-fill deposits (units up to 13 metres) intercalated with floodplain deposits (3 to 12 metres). The channel fills form large composite channel belt complexes passing laterally into splays and shaly floodplain deposits. The splay deposits show dipping accretion of intercalated sandstone and claystone over tens of meters. Palaeocurrent measurements from 3D fluvial cross-beds exposed on the present-day wavecut platform (41 bedforms) show a relatively narrow range (azimuth between N005 and N110) with a mean palaeoflow to the NE (azimuth N068). At Economy Point, the fluvial deposits are interpreted as middle Wolfville Fm. They display identical lithofacies, similar sedimentary architecture and comparable palaeoflow direction (between

N019 and N050) to middle Wolfville deposits located 8 to 10 kilometres away along the southern shore at Burntcoat Head (**Fig. 3A**; Leleu et al., 2010). Floodplain deposits at Economy Point are thicker than in the southern shore sections and are interpreted to represent a more distal equivalent to the distributive fluvial system (e.g. Hartley et al. 2010; Weissmann et al., 2010) that had been documented in the south of the Minas sub-basin (Leleu et al., 2009).

The location of the Economy Point section immediately adjacent to the CCFZ together with the north- to north-eastwards palaeoflow indicators suggests that the Cobequid High did not deflect drainage during middle Wolfville deposition. In addition, the absence of angular, coarse-grained first-cycle, northerly derived material indicates that the rift basin extended north of the present-day northern margin of the Minas sub-basin and was dominated by a transverse fluvial system flowing northward. These observations do not necessarily mean that the CCFZ was not active, but they do indicate that it had no significant syn-depositional topography if sedimentation rate compensated vertical tectonic displacement (sediments filled accommodation space formed by subsidence).

Soley Cove – Red Head section

The Soley Cove section is located 6 km west of the Economy Point section (**Fig.3B**) and is laterally equivalent to the Red Head section cropping out further west. Between Soley Cove and Red Head (over 4 kilometres), the outcrops are continuous and show very thick packages of alluvial-fan deposits interbedded with aeolian deposits up to 10 m in thickness (Hubert & Mertz, 1980; **Figs. 5O, 8**). The rocks are exposed along sea cliffs that are up to 30 metres high and close to vertical. The cliffs are densely faulted hampering detailed logging and correlation. However, since displacement on each fault is limited, an estimation of lateral variation of Alluvial-Fan and Aeolian facies associations was possible (**Fig. 8**).

The Soley Cove section comprises very angular alluvial-fan sediments that grade into finer-grained fan and playa-margin deposits (**Table 1**). Aeolian facies accounts for <1% of the succession in this section; however they are very abundant (approx. 85%) to the west along the cliff between Soley Cove and Red Head. The

Soley Cove – Red Head transect comprises mainly alluvial-fan clast-supported breccia, matrix-supported breccia and pebbly sandstones (deposited by debris flow, hyperconcentrated flow and fluvial processes; **Table 1**). Clasts are very angular and locally derived from basement rocks (meta-granite and diorite and meta-sediments). Aeolian sand was reworked to form part of the matrix to the breccia and pebbly sandstones. The top of the section displays playa-margin facies association considered typical of the Blomidon Formation in particular with the occurrence of the sandpatch fabric sandstones. At Soley Cove, the lowermost part of the section (**Fig. 6**) contains thick packages of coarse alluvial-fan deposits (clast- and matrix- supported breccia and pebbly sandstones), locally interbedded with thin playa-margin beds, passing upwards into dominantly playa-margin facies. The uppermost part of the section displays thick distal-fan deposits (granule-bearing sandstones and ripple-laminated sandstones) interbedded with sandpatch sandstones and claystones punctuated by thin, coarse alluvial-fan deposits.

The relative volume of preserved aeolian deposits (from 1% to 50 % and then to 85% of exposure) increases to the west, whilst the amount of alluvial-fan deposits decreases (**Fig. 8**). Aeolian-dune deposits preserved close to Soley Cove are up to 8 m thick, while the westernmost aeolian beds close to Red Head form a composite aeolian package up to 27 m thick with the thickest individual aeolian bed of 4 metres. Thickness of alluvial-fan beds varies from 1 to 3 m but variations are not organised in a preferential direction. However aeolian beds are more frequently punctuated by fan deposits towards the east (Soley Cove where they dominate largely) and the volume of alluvial-fan sediments overall decreases to the west (**Fig. 8**).

Correlation across the Minas sub-basin

The base of the Blomidon Formation crops out north of the Medford section (in SW Minas sub-basin) and at Soley Cove, on the northern side of the present-day Minas sub-basin (**Fig. 3A**). At Medford the Wolfville/ Blomidon boundary is marked by the cessation of confined channelized fluvial deposits and the dominance of sheetflood and playa deposits forming the Playa-Margin facies association (Leleu & Hartley, 2010). Deposition of numerous fined-grained unconfined flows occurred and shallow lakes developed occasionally in the area but eventually dried up as indicated by aeolian adhesion ripples on the wet surface. Aeolian dunes are preserved beneath the lowermost Blomidon Formation at the Medford section where the last aeolian bed is recorded in the southern stratigraphy (11 meters above the contact with the upper Wolfville Formation; **Fig. 9**). In the northern sections (Soley Cove-Red Head section) aeolian dunes were replaced progressively by alluvial-fan and playa sedimentation to the east (**Fig. 10**). Consequently playa-margin deposits are the predominant facies in the south (Medford section) with playa and shallow-lake deposits dominating the northern stratigraphy (Gould, 2001) as unconfined flows from the fans decreased progressively in grain size and eventually stopped. Typically lithofacies distribution changes significantly across the basin and estimating an age for the aeolian and alluvial-fan deposits is not straightforward, and consequently direct lithostratigraphic correlation cannot be used. However we have used the termination of channelized fluvial deposition and the occurrence of specific playa deposits to define the boundary between Wolfville and Blomidon Fm (Leleu & Hartley, 201), we also suggest using the termination of aeolian deposition across the basin as recording a new phase in the basin fill. Indeed aeolian deposits are not present in the uppermost stratigraphy and can be considered a marker for a change in the basin stratigraphy. We suggest therefore that aeolian dune and alluvial-fan deposits may also represent the lowermost Blomidon Formation and older deposits in the northern sections. Whilst this approach cannot be considered accurate from a chronostratigraphic perspective, it is based on the idea of correlating basin-wide changes in facies that reflect climatic variability, an approach that has been used previously in arid continental successions (e.g. George & Berry 1993).

DRAINAGE EVOLUTION

The tectono-sedimentary linkage between the Minas and the Chignecto sub-basins and the amount and timing of displacement along the CCFZ are not well understood. Here we summarise the temporal development of the structure based on the sedimentary record (i.e. facies distribution, architecture and palaeoflow) (**Fig. 11**).

Carnian: During Carnian times, fluvial deposits of the Wolfville Formation started to be preserved in the southern Minas area, corresponding to a major period of basin enlargement (Leleu & Hartley, 2010). These fluvial systems flowed northwards from the southern rift shoulder uplands into the Minas sub-basin. They formed transverse fluvial systems that were either connected to an axial trunk river in the Fundy and Chignecto sub-basins or terminated in a playa basin (**Fig. 11A**). The fluvial palaeoflows measured in the southern Minas sub-basin indicate that the fluvial system was flowing to the NE (means between N019° and N051°). At Economy Point, located about 8 kilometres downstream, the mean palaeocurrent direction of the flow is to N068°. The range of palaeoflows presents a similar fluvial direction to the NE. It is likely that the Cobequid High was not present at the time although one could argue that there is a little change in direction that could reflect a slight deviation of the fluvial system. So it is most likely that there was no major topography along the CCFZ prior to latest Wolfville or earliest Blomidon deposition but it is possible that a local change in subsidence related to CCFZ activity might have influenced the main river path.

Early Norian: Less data are available on the transition between the Wolfville and Blomidon Formations during early Norian times (Olsen et al., 2005). In the southwest Minas sub-basin sections, fluvial systems were smaller and terminal, comprising feeder channels, terminal splay and mudflat deposits (Leleu and Hartley, 2010). On the northern side of the Minas sub-basin, aolian sediments were abundant at that time and aeolian deposits are locally thick (Red Head section in the Minas sub-basin; Hubert & Mertz, 1984). Simultaneously, the development of alluvial fans implied that the Cobequid highlands formed an intra-basinal high and sourced the alluvial-fan deposits (**Fig. 11B**). In consideration of the amount of polished quartz sand of aeolian origin within the fan successions, it is likely that aeolian sand was reworked as the matrix for debris-flow processes suggesting that aeolian dunes or sand were also present on the top of the horst structure.

Mid Norian-Rhaetian During early Blomidon deposition, only a few aeolian deposits are preserved and eventually no aeolian deposits are preserved at all later in the Blomidon Formation (late Norian and Rhaetian) (**Fig. 11C**). The Fundy and Minas sub-basins are dominated by splay and shallow-lake deposits and become increasingly evaporitic at some stratigraphic intervals, attesting to periods of more intense evaporation. The playa-lake system was very extensive across the entire Fundy Basin and the Cobequid High might have already been buried as no alluvial-fan deposits are recorded in the upper part of the Blomidon Formation along the CCFZ. Channel-fill deposits are located along the southern shore of the Minas and Fundy sub-basins

(Gould, 2001; Leleu & Hartley, 2010) and we suggest therefore that, although relatively minor, the main fluvial systems feeding the basin were sourced from the south.

DISCUSSION

Drainage and intra-basinal faulting in the Fundy rift basin

Previous models of drainage development in the Minas sub-basin considered the Cobequid High as a long-lived structure in the Fundy basin with rivers flowing northwards from the rift shoulder and southwards from a long-lived horst structure across the Minas sub-basin and being deflected to the east to join a major trunk river system (Hubert and Mertz, 1984; Hubert & Forlenza, 1988). Here, we demonstrate however that the Cobequid High was not developed as a topographic high during deposition of the lower and middle Wolfville Fm, and most likely not present prior to then either (Leleu & Hartley, 2010). The presence of the intrabasinal CCFZ has major implications for the drainage organization in the basin history. The sedimentary architecture is complex along the CCFZ where deposits are highly faulted, but the assessment of facies distribution and palaeoflow reconstruction within a stratigraphic framework provide evidence for the timing of uplift of an intrabasinal topographic high by the CCFZ. Growth strata were reported along the CCFZ (Withjack et al. 2010), but it is clear that topography was created only during Norian times, when alluvial-fan deposition commenced. The earlier phase of sedimentation in the Minas sub-basin shows a fluvial system flowing consistently to the northeast suggesting the absence of a topographic high. Thus despite the existence of growth strata along the CCFZ, the absence of marked topography prior to alluvial-fan sedimentation means that fluvial sedimentation rate compensated for the accommodation space created by local tectonics. A major tectonic event created the horst structure which fed alluvial fans at some point in the basin stratigraphy (estimated during the early Norian). The stratigraphy close to the CCFZ shows that alluvial fans aggraded through time before retrograding and finally disappeared. Fine-grained lacustrine/ playa deposits were then dominant in the whole basin and even close to the CCFZ. This suggests that the horst structure became buried by the Blomidon low-energy lacustrine/ playa deposits. As the sedimentation rate for the Blomidon Fm is particularly low (200 meters in the Minas sub-basin for 15 My), it is likely that there was no more vertical displacement along the CCFZ and that most growth strata imaged in seismic line belong to the Wolfville Formation and the base of the Blomidon Formation.

Aeolian bed preservation within fluvial deposits

Aeolian sediments are well preserved in the upper Wolfville Fm and at the transition into the lowermost Blomidon. From south to north the preservation of aeolian facies increases towards the CCFZ. Preservation of aeolian beds implies that sediments were buried beneath a regional base-level that normaly equates to the groundwater table in aeolian successions (Koçurek & Havholm, 1993). This occurs either through subsidence and subsequent relative rise in groundwater table or by an absolute rise in water table following a change in climate (Koçurek 1981; Mountney et al., 1999). The most obvious mechanism for aeolian bed preservation in this case is tectonic subsidence as preserved thickness increase towards the CCFZ and thins to the south. In addition, aeolian beds are interbedded with alluvial-fan deposits indicating activity on the CCFZ. Therefore the combination of fan deposition and preservation of aeolian deposits seems to indicate that vertical movement along the CCFZ accelerated around the early Norian. In the southern margin of the Minas sub-basin, preserved aeolian beds are thin (2 meters) and intercalated with either fluvial sandstone or lacustrine mudstones punctuated by exposure surfaces with desiccation cracks (Leleu & Hartley, 2010). There is no indication of an elevated groundwater level in the basin such as adhesion ripples or wavy laminated sandstone (Koçurek, 1981) until upper units within the basin stratigraphy (Blomidon Fm). Interestingly, no aeolian beds are preserved higher in the stratigraphy, i.e. in Blomidon Fm, when a high water-table is recorded by adhesion ripples (with sand-patch fabric). Thus preservation of both the intercalated aeolian sediments and alluvial-fan deposits corroborate an increase in activity of the CCFZ during deposition in the basin and no absolute higher water-table associated with a change in climatic regime. This interpretation supports the idea that the development of a wide lacustrine rift basin (with little fluvial input) following the deposition of large fluvial systems in the rift basin is not climatically driven. The decrease in sediment supply in the fluvial systems has been interpreted to reflect a decrease in fluvial gradient due to progressive erosion through time and no rejuvenation of rift-shoulder relief (Smoot 1991; Leleu & Hartley 2010) possibly related to a decrease in tectonic activity (final phase of Triassic rifting). Nevertheless, growth structures along the main boundary faults of the Fundy Basin attest that rifting was still active and large-scale tectonics occurred in the Central Atlantic domain.

In summary, the CCFZ segmented the initial large rift basin and formed an intrabasinal horst that fed the alluvial fans. The accumulation and preservation of aeolian dunes adjacent to the fault scarp along the Cobequid High, especially to the west of the study area, were probably favoured by fault-induced subsidence. Accumulation of aeolian dunes mainly south of the Cobequid high and close to the fault scarp suggests that either the horst represented a topographic barrier to aeolian dunes or formed a wind shadow that favoured local accumulation of aeolian sands. The mean palaeowind is to the SE and therefore it is more likely that the Cobequid High acted as a wind shadow. This interpretation is consistent with the presence of windblown sand in the fan catchment that was reworked by floods to form the matrix of debris flows and fluvial pebbly sandstones. The occurrence of synchronous alluvial-fan and aeolian deposits validates the development of the northern topographic high prior to deposition.

CONCLUSIONS

The facies types, distribution and palaeoflow data from Upper Triassic alluvial and aeolian deposits in the Fundy Basin along the CCFZ are used to determine timing of fault activity and suggest that an initially large Carnian rift basin was segmented by an intrabasinal horst during Norian times. A Carnian transverse fluvial system flowing to NE does not show major diversion and suggests that no topographic high was present at that time. Alluvial-fan deposits intercalated upwards with typical Norian playa deposits recorded the development of the intrabasinal horst. Fining-upward fan deposits and development of fine-grained playa successions suggest that topography was not renewed and was eventually buried by sediment aggradation within the basin. Simultaneous with alluvial-fan development, aeolian dunes were preserved adjacent to the CCFZ. Aeolian accumulation was probably accentuated due to the fault scarp acting as a wind shadow with preservation of aeolian deposits promoted by subsidence beneath a regional erosional base level.

Alluvial-fan deposits were sourced from local relief of the intrabasinal horst with very angular clasts transported mainly by debris and hyperconcentrated flows. Some of the fans forming the CCFZ piedmont flowed through the dune field mainly located to the west. Aeolian sands form a large fraction of the matrix for coarse-grained fan deposits, indicating that windblown sand was trapped onto the proximal domains of the fan or within the fan catchments before being remobilised by alluvial processes.

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Figure 1: Introduction to the Fundy Basin; (A) Map of the Fundy Basin showing sub-basins, major faults (modified from Wade et al., 1996) and location of cross-sections: (B) Cross-section of the Chignecto and

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Figure 5: Lithofacies examples: (A) clast-to-matrix supported breccia showing a chaotic and poorly sorted fabric (*lithofacies 1*) overlain by pebbly sandstones (*lithofacies 3*); (B) horizontal beds of clast-supported breccia (*lithofacies 1*), the basal bed is normally graded, the bed in the center is inversely graded with an intercalated 15-cm-thick bed of matrix-supported breccia (*lithofacies 2*); (C) thick basal matrix-supported breccia (*lithofacies 1*) overlain a by 30-cm-thick, weakly erosive clast-supported breccia (*lithofacies 1*) and intercalated with thin beds of clast-supported and matrix-supported breccia, clast-supported breccias show long-axis imbrication (flow to the left); (D) very thin beds (< 10cm) of intercalated clast-supported and matrix-supported breccias, clast-supported breccias show long-axis imbrication (flow to the right); (E) thick matrix-supported breccia (*lithofacies 2*) overlain by pebbly sandstones showing horizontal bedding (*lithofacies 3*); (F) close-up showing coarse well-rounded (white) grains forming the matrix of alluvial-fan deposits. The coarse grains are of aeolian origin; (G) amalgamated beds of granule-bearing sandstones

(*lithofacies 4*). Beds are 3 cm thick and slightly erosive with thin pebble lags; (H) granule-bearing sandstone beds with centimetre-scale claystone partings (*lithofacies 4*) and one 3-cm-thick bed (black arrows) of isolated finer-grained sandsheet (*lithofacies 6*) is interbedded within the granule-bearing sandstone package; (I) sandpatch heterolithic sandstones (*lithofacies 5*) show deformed isolated sandy ripples within a matrix of dark silty clay with floating fine to coarse grains. Ripples are composed of a mixture of fine and coarse grains; (J) sandpatch hererolithic sandstones interbedded with granule-bearing sandstone show a wavy and poorly defined basal contact with underlying sandstones; (K) thick package of ripple-laminated sandstones (*lithofacies 8*) with centimetre-scale basal erosion with wavy upper contacts. Beds are often amalgamated but thin clay partings are locally preserved; (L) ripple-laminated sandstones (*lithofacies 8*) show ripples in the upper part and claystone drapes; (M) interference ripples indicating wave reworking of current ripples, preserved beneath a few centimetres of claystones (*lithofacies 11*); (N) dipping sandy foresets in heterolithic claystones (*lithofacies 10*) (O) aeolian sandstones with steep foresets, highlighted by white arrows, and intercalated with alluvial-fan deposits. Black arrows highlight the erosional contact of alluvial-fan deposits.

Figure 6: Detailed sedimentary section at Soley Cove. The main part of the section shows thick alluvial-fan deposits that eventually fine upward (retrograding) and are intercalated with playa deposits.

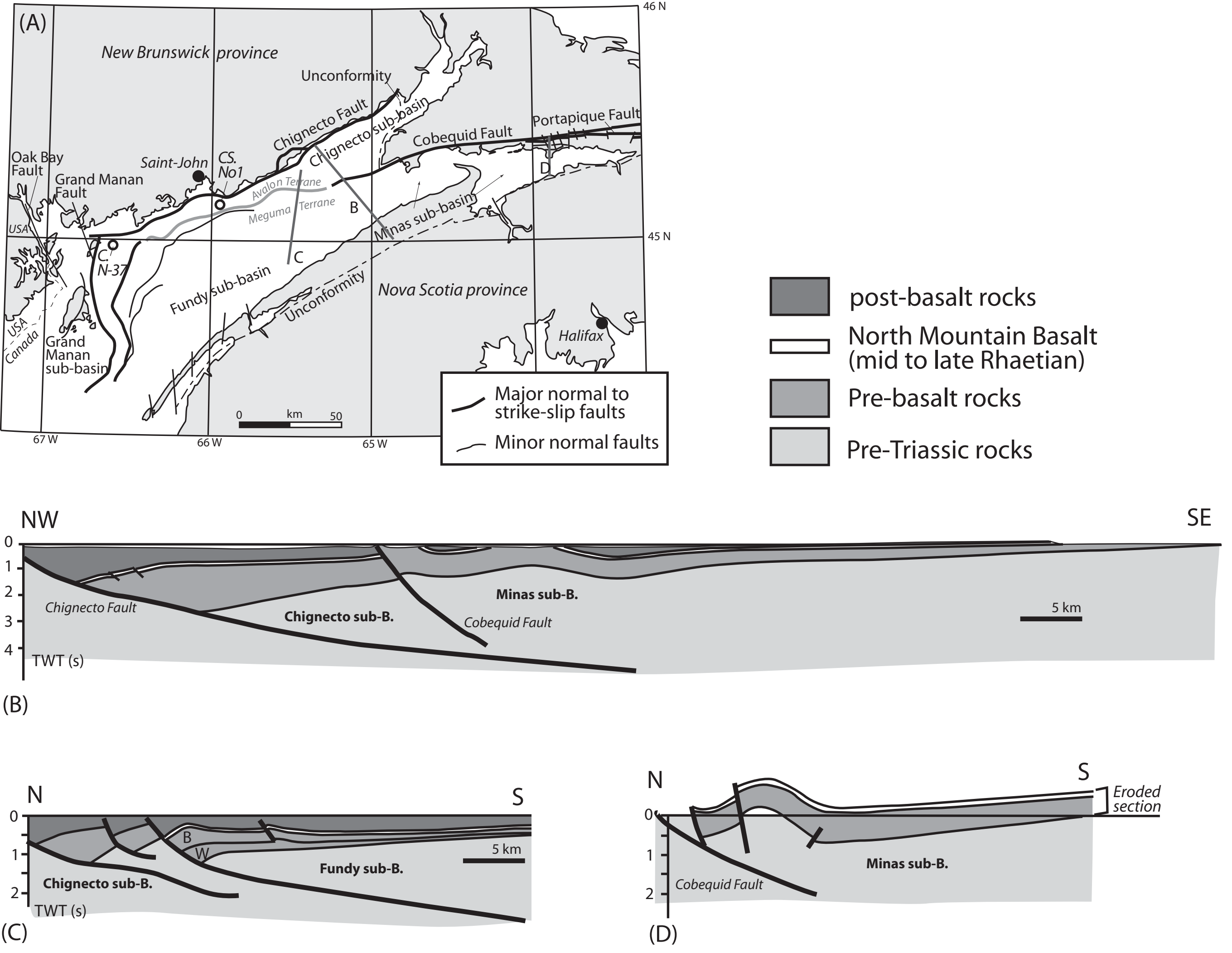
Figure 7: Detailed sedimentary sections at Economy Point (4 sections across 1.5 km). The sedimentary architecture shows channel-fill sandstones forming a large composite channel-belt complex intercalated with levees and silty or shaly floodplain deposits. Palaeocurrents measured from 41 fluvial cross-bed strike gives a mean palaeoflow to the NE.

Figure 8: Schematic facies architecture of the highly faulted cliffs between Red Head and Soley Cove section (roughly 4 km). Proportion of aeolian (white) and alluvial-fan (pebbles) sediments is represented. Shaded conglomeratic packages are given in order to represent schematic initial architecture of interbedded aeolian and alluvial-fan deposits but vertical small-displacement faults prevent a realistic reconstruction of primary sedimentary architecture.

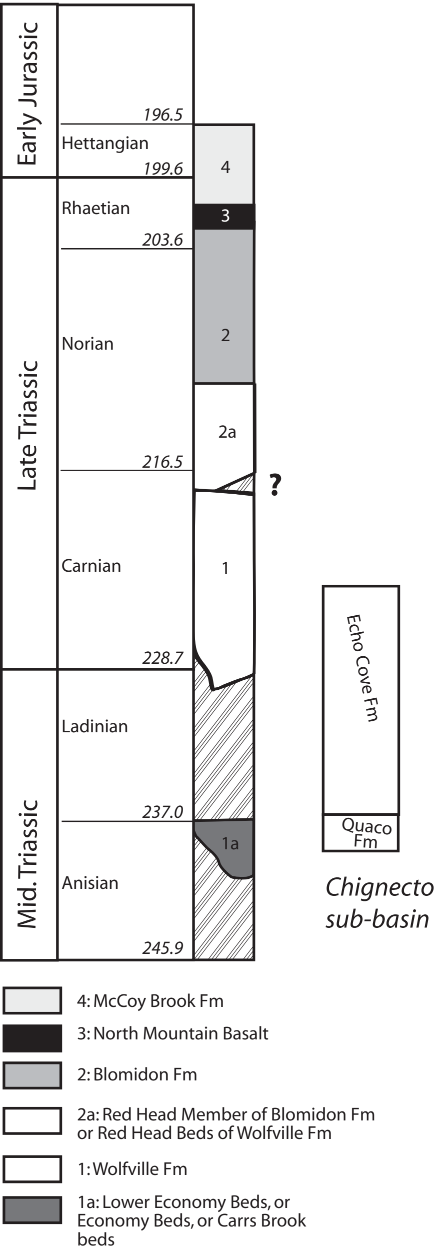
Figure 9: Correlation across the Minas sub-basin showing facies variability from south to north. Onset of occurrence of finer-grained facies (such as sand-patch-fabric sandstones) and disappearance of aeolian beds are used as time markers.

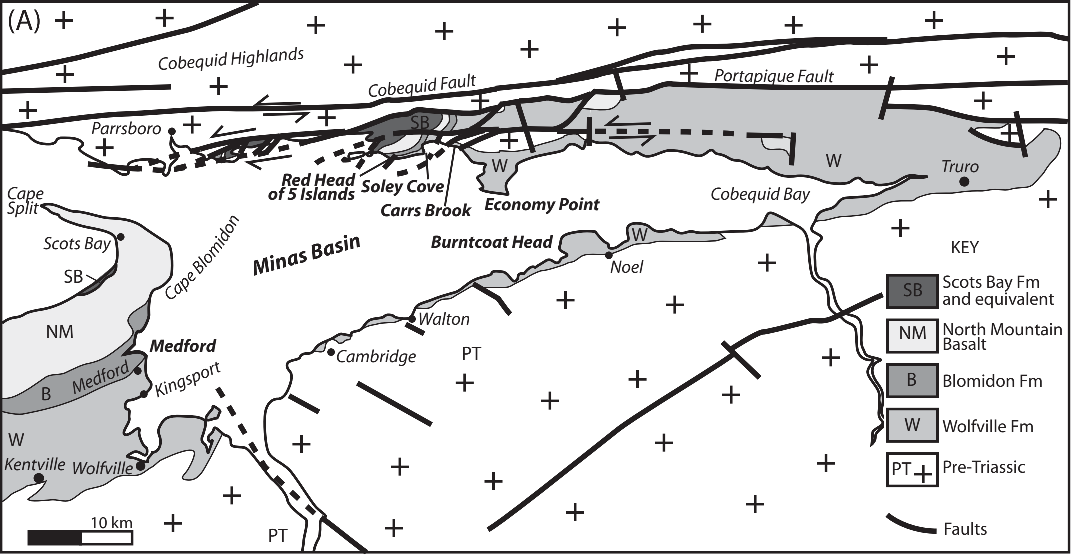
Figure 10: Sedimentary model for the period of horst development on the northern edge of the Minas sub-basin, corresponding to the transition of upper Wolfville Formation and lowermost Blomidon Formation. The depositional system was highly variable: close to the northern topography and along the fault scarp where alluvial fans interfingered with aeolian dunes, abundant to the west. Aeolian sand was trapped in the small drainage basins of the alluvial fans and was reworked into the matrix of fan deposits. Aeolian sand was probably deposited on the downwind slope of the horst structure as wind mainly blew from the NW. Part of the windblown sand was trapped in the catchment while most was deposited as aeolian dunes in the basin along the fault scarp. In the southern part of the Minas sub-basin (Leleu & Hartley, 2010) aeolian dunes interfingered with fluvial channels, terminal splays and shallow-lake deposits.

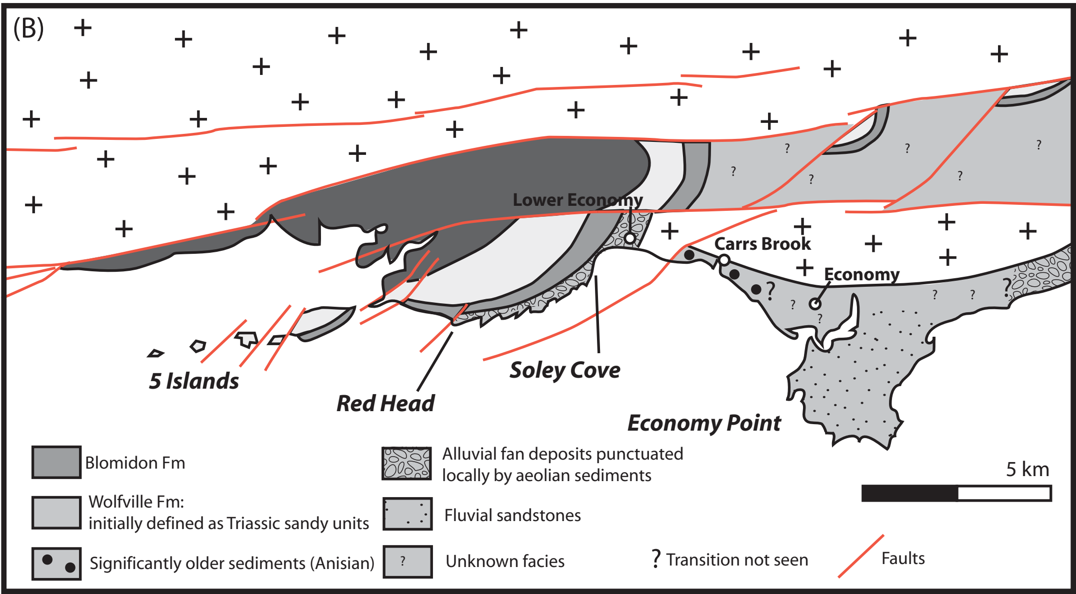
Figure 11: Triassic drainage evolution in the Fundy Basin; (A) Carnian (deposition of lower and middle Wolfville Fm), the main depositional systems are transverse fluvial systems sourced from the hanging-wall shoulder (south). The Cobequid High was not present. The longitudinal drainage is restricted to the northern side of the basin in the Chignecto sub-basin; (B) early Norian (deposition of upper Wolfville Fm and lowermost Blomidon Fm), the fluvial system of the hanging-wall decreased in size and terminated with splays into a playa-type lake. An intrabasinal high emerged along the Cobequid Fault and small alluvial fans developed. Aeolian dunes were relatively abundant in the basin and especially close to the fault scarp; (C) upper Norian and lower Rhaetian (deposition of Blomidon Fm), the fluvial system decreased in size and splay deposits dominated along the basin edge. Aeolian dunes and alluvial fans gradually disappeared along the Cobequid High, suggesting that it was overlapped by the lacustrine facies. The playa facies eventually became evaporitic in places.

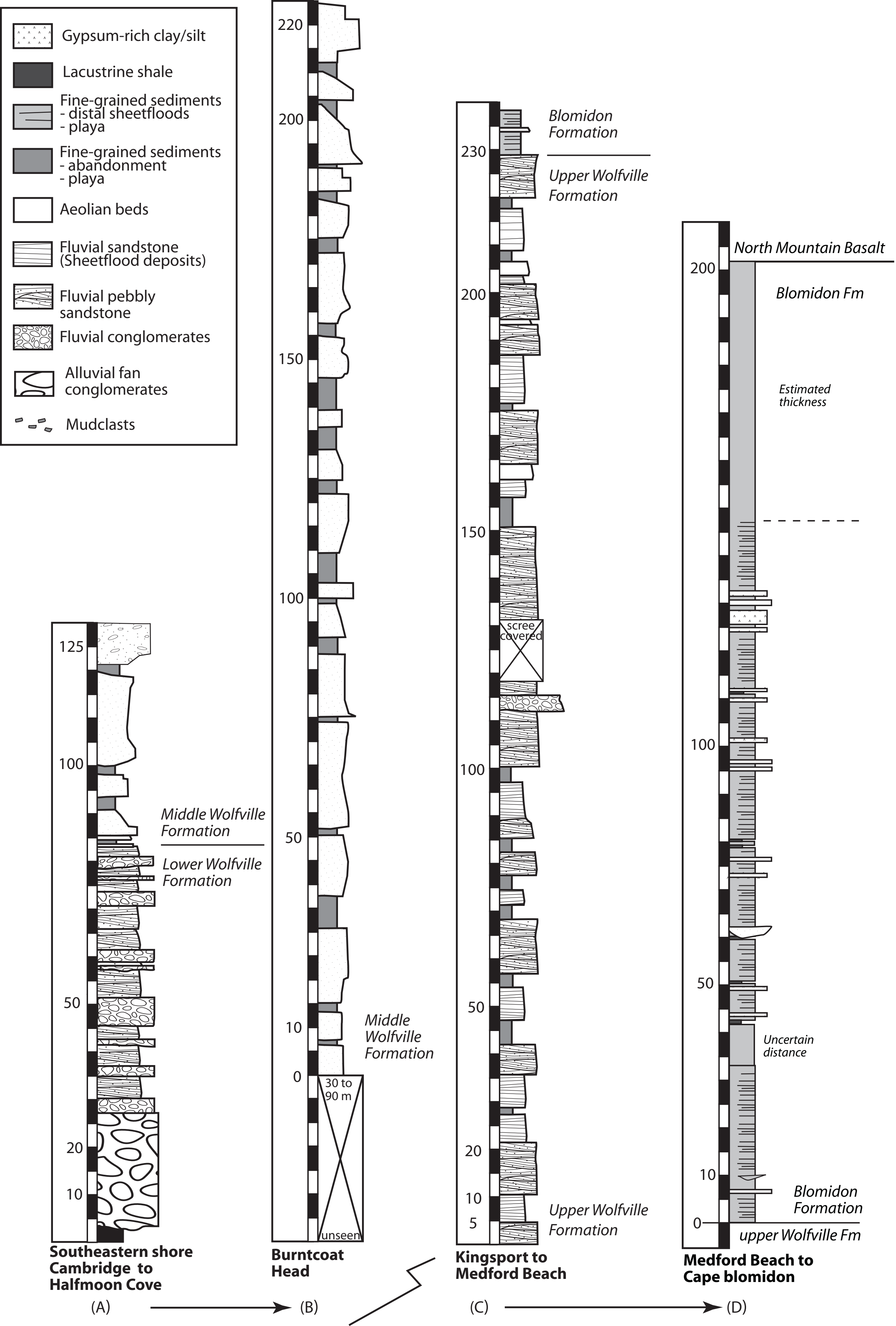


(A)
New Brunswick province
Unconformity
Chignecto Fault
Chignecto sub-basin
Cobequid Fault
Portapique Fault
Oak Bay Fault
Grand Manan Fault
Saint-John
CS. No1
Avalon Terrane
Meguma Terrane
Minas sub-basin
USA
C. N-37
Fundy sub-basin
Unconformity
Nova Scotia province
USA
Canada
Grand Manan sub-basin
Halifax
0 km 50
46 N
45 N
67 W
66 W
65 W
B
C
D
Major normal to strike-slip faults
Minor normal faults
post-basalt rocks
North Mountain Basalt (mid to late Rhaetian)
Pre-basalt rocks
Pre-Triassic rocks
NW
SE
Chignecto Fault
Minas sub-B.
Chignecto sub-B.
Cobequid Fault
5 km
TWT (s)
(B)
N
S
B
W
Fundy sub-B.
Chignecto sub-B.
5 km
TWT (s)
(C)
N
S
Eroded section
Minas sub-B.
Cobequid Fault
(D)

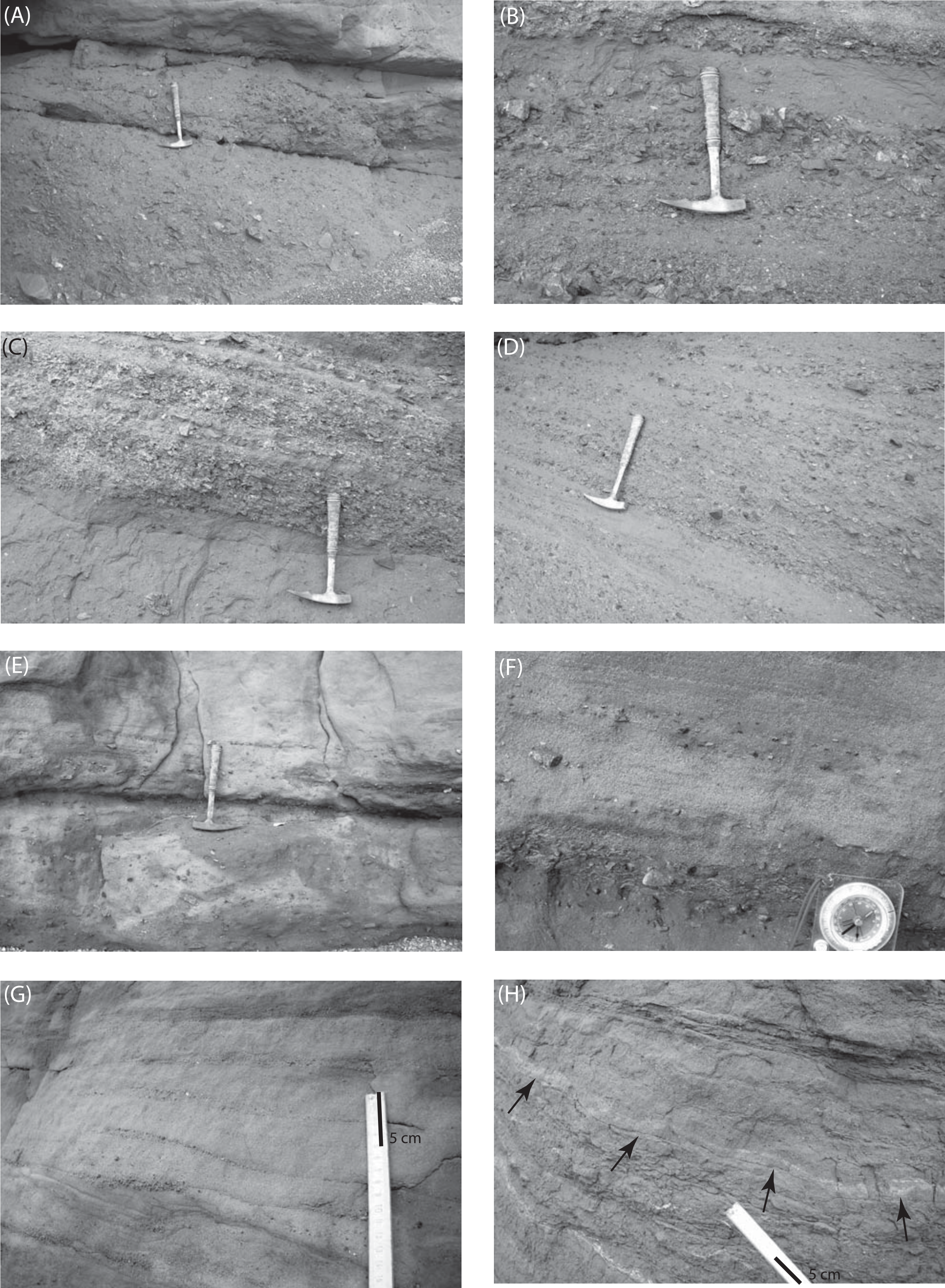

Early Jurassic
Late Triassic
Mid. Triassic
Hettangian
Rhaetian
Norian
Carnian
Ladinian
Anisian
196.5
199.6
203.6
216.5
228.7
237.0
245.9
4
3
2
2a
1
1a
?
Echo Cove Fm
Quaco Fm
Chignecto sub-basin
4: McCoy Brook Fm
3: North Mountain Basalt
2: Blomidon Fm
2a: Red Head Member of Blomidon Fm or Red Head Beds of Wolfville Fm
1: Wolfville Fm
1a: Lower Economy Beds, or Economy Beds, or Carrs Brook beds

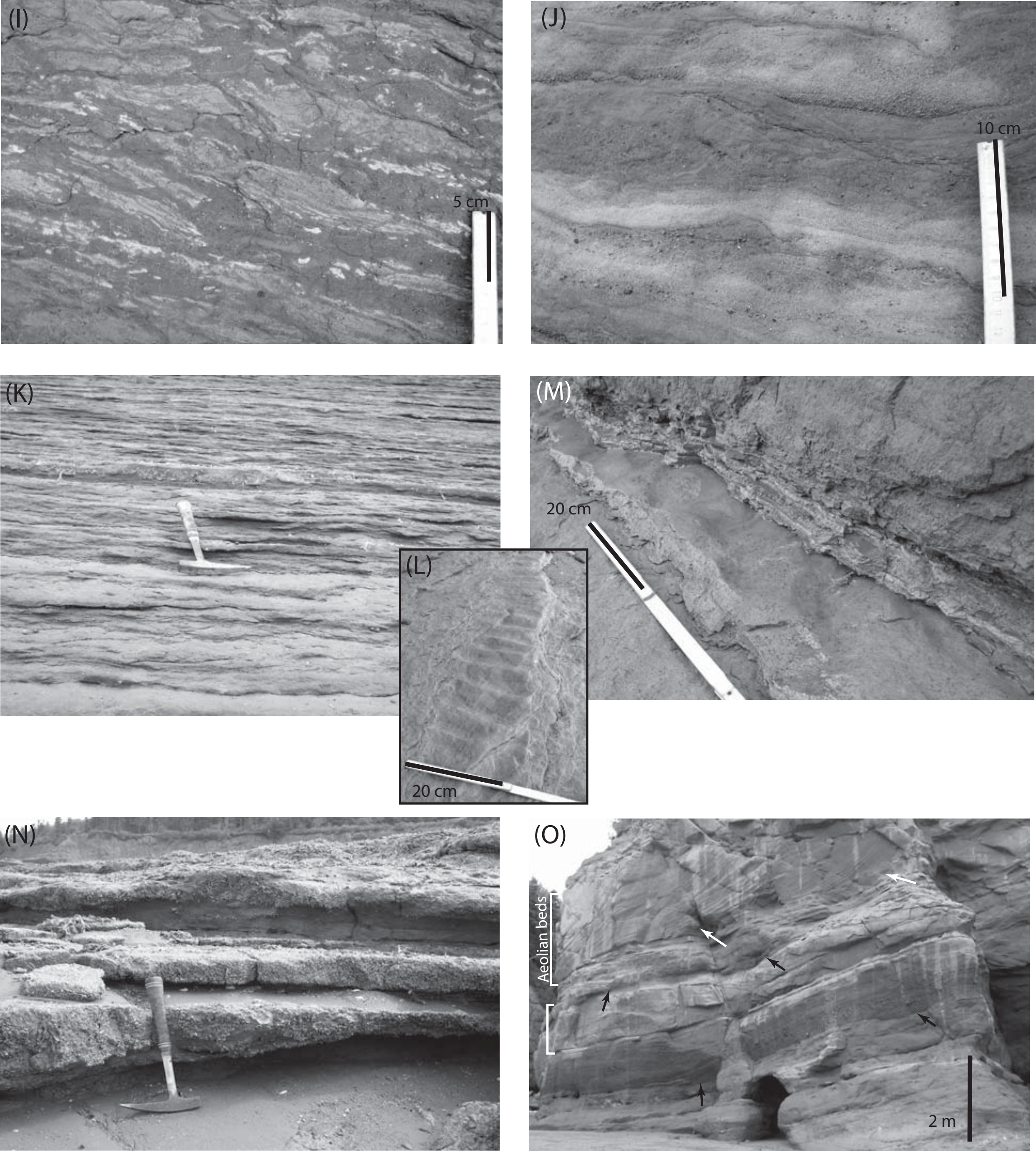

(A)
Cobequid Highlands
Cobequid Fault
Portapique Fault
Parrsboro
SB
W
Truro
Cape Split
Red Head of 5 Islands
Soley Cove
Carrs Brook
Economy Point
Cobequid Bay
Scots Bay
Cape Blomidon
Minas Basin
Burntcoat Head
Noel
KEY
SB
NM
Medford
Walton
Cambridge
PT
Medford
Kingsport
B
W
Kentville
Wolfville
10 km
PT
SB Scots Bay Fm and equivalent
NM North Mountain Basalt
B Blomidon Fm
W Wolfville Fm
PT Pre-Triassic
Faults


(B)
Lower Economy
Carrs Brook
Economy
5 Islands
Red Head
Soley Cove
Economy Point
Blomidon Fm
Wolfville Fm: initially defined as Triassic sandy units
Significantly older sediments (Anisian)
Alluvial fan deposits punctuated locally by aeolian sediments
Fluvial sandstones
Unknown facies
? Transition not seen
5 km
Faults

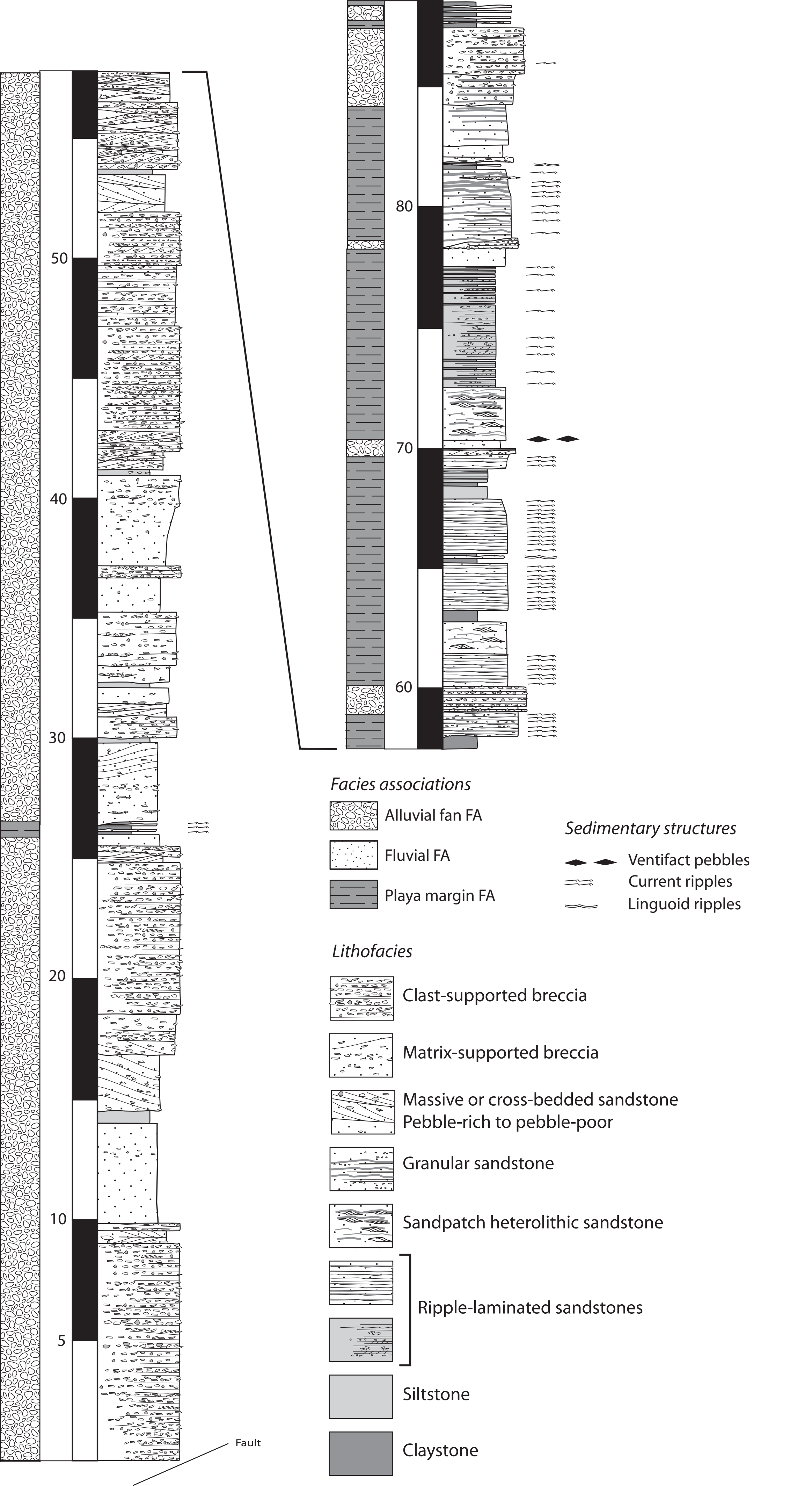


Gypsum-rich clay/silt
Lacustrine shale
Fine-grained sediments - distal sheetfloods - playa
Fine-grained sediments - abandonment - playa
Aeolian beds
Fluvial sandstone (Sheetflood deposits)
Fluvial pebbly sandstone
Fluvial conglomerates
Alluvial fan conglomerates
Mudclasts
Middle Wolfville Formation
Lower Wolfville Formation
Southeastern shore Cambridge to Halfmoon Cove
(A)
30 to 90 m
unseen
Middle Wolfville Formation
Burntcoat Head
(B)
Blomidon Formation
Upper Wolfville Formation
scree covered
Upper Wolfville Formation
Kingsport to Medford Beach
(C)
North Mountain Basalt
Blomidon Fm
Estimated thickness
Uncertain distance
Blomidon Formation
upper Wolfville Fm
Medford Beach to Cape blomidon
(D)

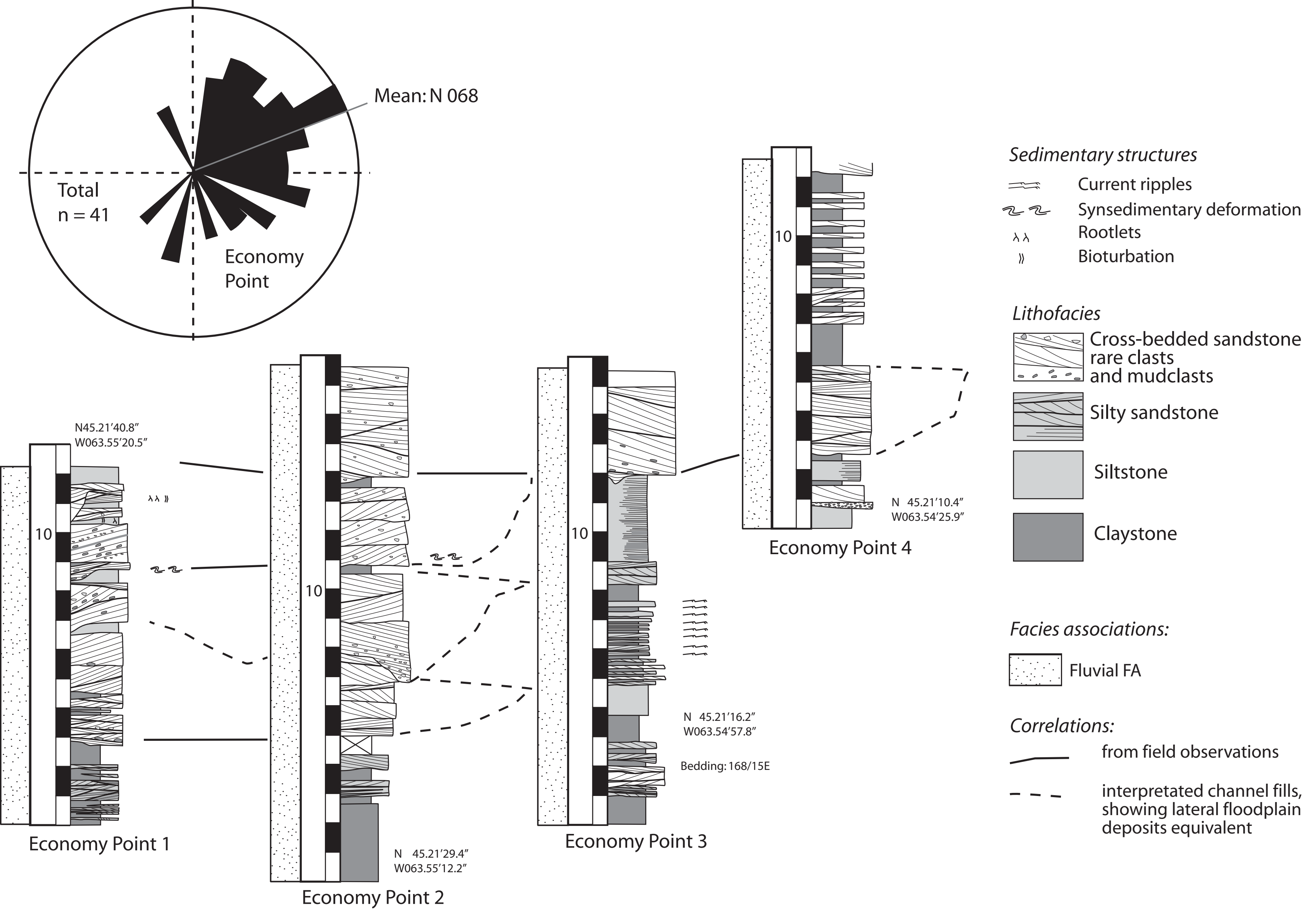

(A)
(B)
(C)
(D)
(E)
(F)
(G)
5 cm
(H)
5 cm



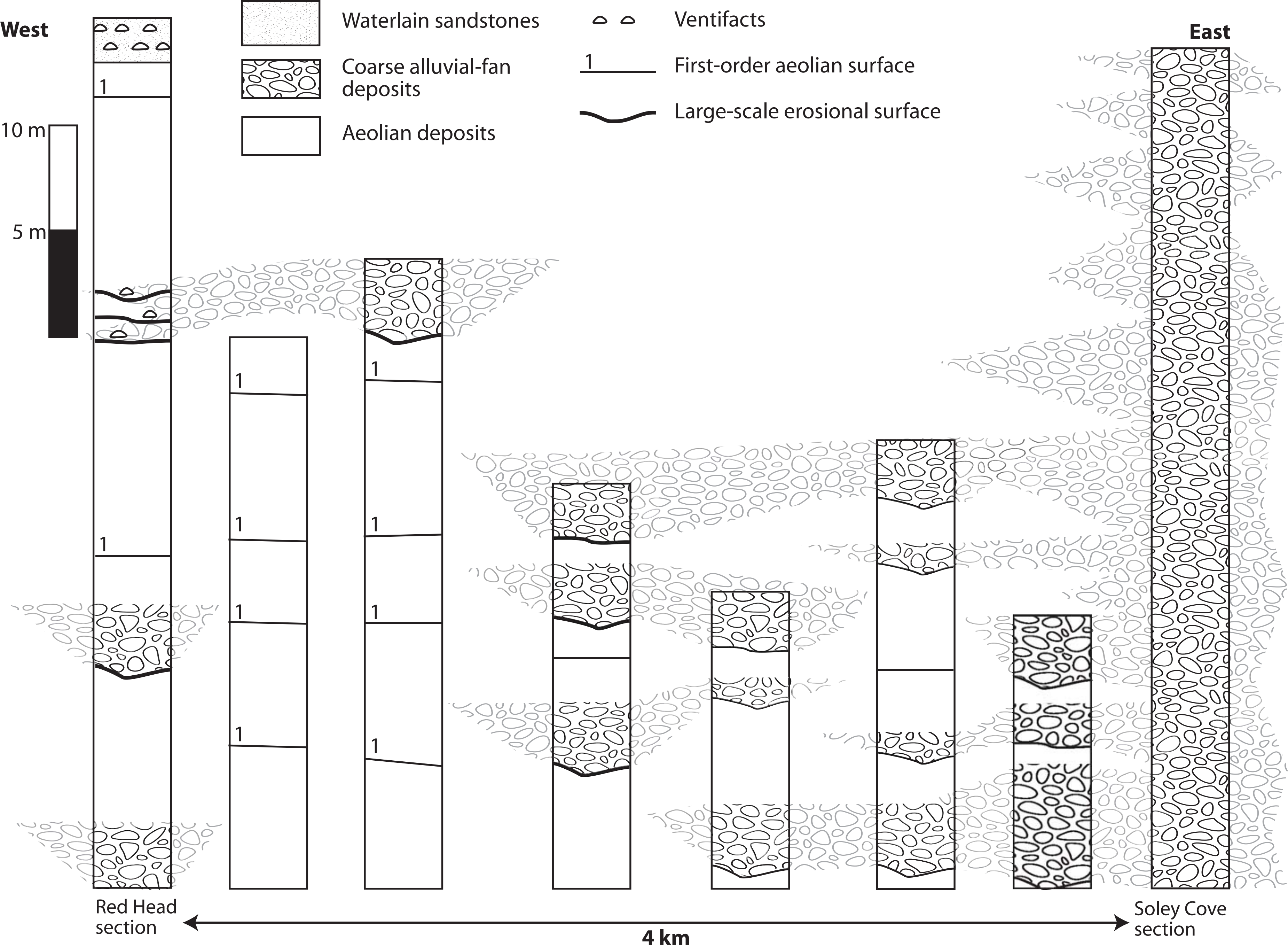
(I)
5 cm
(J)
10 cm
(K)
(M)
20 cm
(L)
20 cm
(N)
(O)
Aeolian beds
2 m



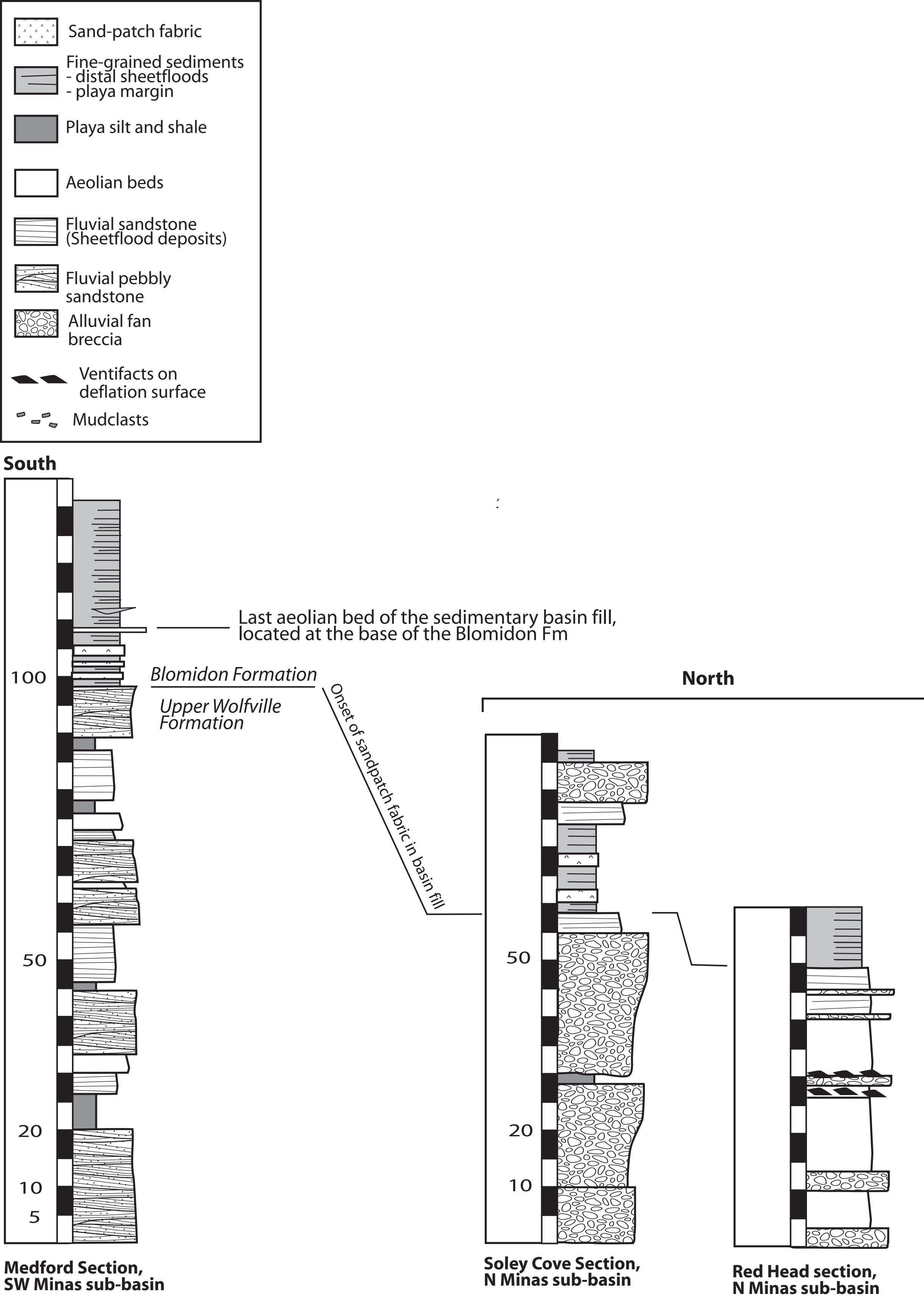
80
70
60
50
40
30
20
10
5
Fault
Facies associations
Alluvial fan FA
Fluvial FA
Playa margin FA
Sedimentary structures
Ventifact pebbles
Current ripples
Linguoid ripples
Lithofacies
Clast-supported breccia
Matrix-supported breccia
Massive or cross-bedded sandstone
Pebble-rich to pebble-poor
Granular sandstone
Sandpatch heterolithic sandstone
Ripple-laminated sandstones
Siltstone
Claystone



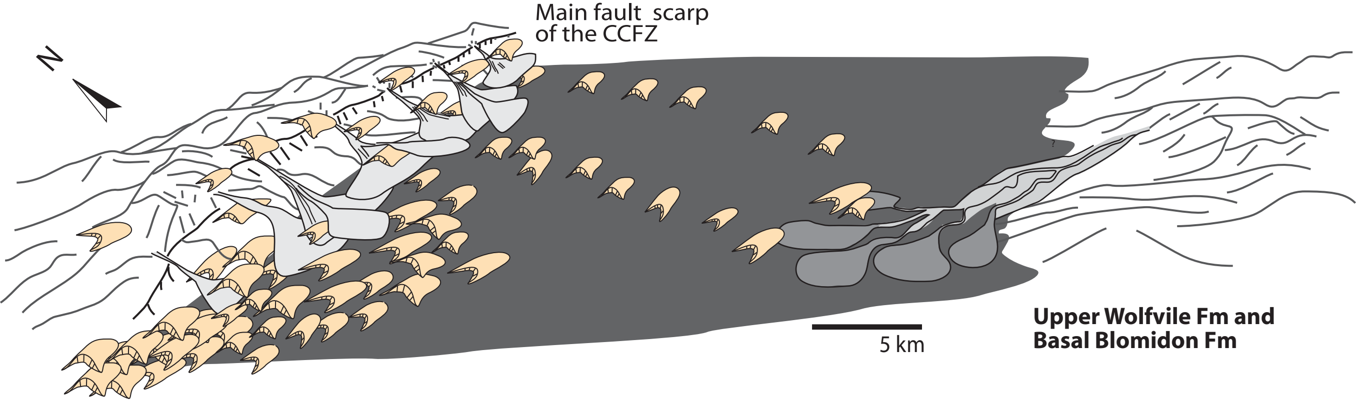
Mean: N 068
Total
n = 41
Economy
Point
Sedimentary structures
Current ripples
Synsedimentary deformation
Rootlets
Bioturbation
Lithofacies
Cross-bedded sandstone
rare clasts
and mudclasts
Silty sandstone
Siltstone
Claystone
Facies associations:
Fluvial FA
Correlations:
from field observations
interpretated channel fills,
showing lateral floodplain
deposits equivalent
N45.21'40.8"
W063.55'20.5"
10
Economy Point 1
10
N 45.21'29.4"
W063.55'12.2"
Economy Point 2
10
N 45.21'16.2"
W063.54'57.8"
Bedding: 168/15E
Economy Point 3
10
N 45.21'10.4"
W063.54'25.9"
Economy Point 4

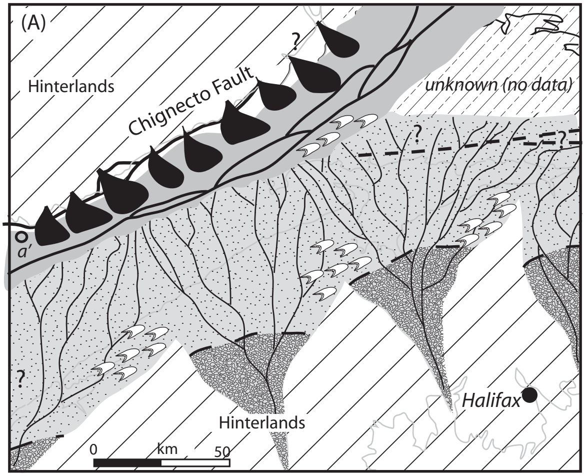


West
East
Waterlain sandstones
Coarse alluvial-fan deposits
Aeolian deposits
Ventifacts
First-order aeolian surface
Large-scale erosional surface
10 m
5 m
1
Red Head section
Soley Cove section
4 km

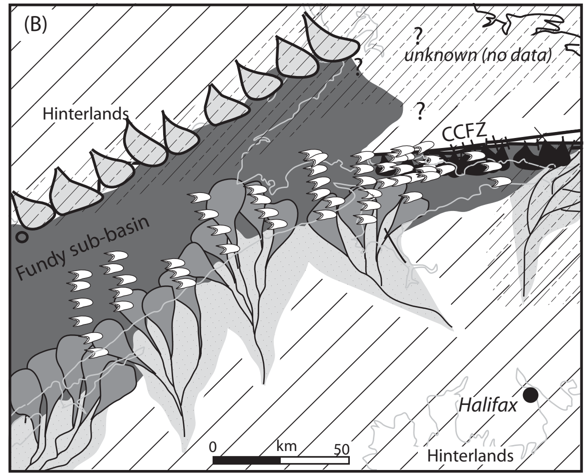


Sand-patch fabric
Fine-grained sediments
- distal sheetfloods
- playa margin
Playa silt and shale
Aeolian beds
Fluvial sandstone
(Sheetflood deposits)
Fluvial pebbly
sandstone
Alluvial fan
breccia
Ventifacts on
deflation surface
Mudclasts
South
Last aeolian bed of the sedimentary basin fill,
located at the base of the Blomidon Fm
Blomidon Formation
Upper Wolfville
Formation
Onset of sandpatch fabric in basin fill
North
100
50
20
10
5
50
20
10
Medford Section,
SW Minas sub-basin
Soley Cove Section,
N Minas sub-basin
Red Head section,
N Minas sub-basin

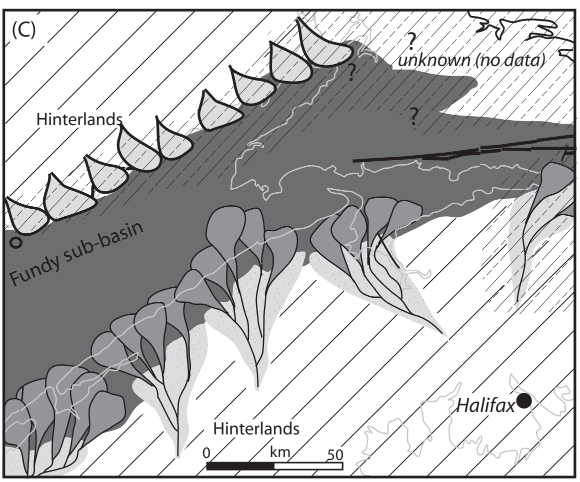

Main fault scarp
of the CCFZ
N
5 km
Upper Wolfvile Fm and
Basal Blomidon Fm



Wolfville Fm (Carnian)



uppermost Wolfville Fm/ lowermost Blomidon Fm (early Norian)



Blomidon Fm (Norian to Rhaetian)