Transtensional arm of the early Mesozoic Fundy rift basin: Penecontemporaneous faulting and sedimentation

Paul E. Olsen, Roy W. Schlische
Department of Geological Sciences and Lamont-Doherty Geological Observatory of Columbia University
Palisades, New York 10964

ABSTRACT

Formed as a major right-lateral fault zone during Paleozoic collisional orogenies and reactivated as a left-oblique system during the early Mesozoic, the east-striking Minas fault zone of Atlantic Canada controlled adjacent sedimentation in the Fundy rift basin, producing a series of synsedimentary microbasins. Northeast-striking boundary faults of the Fundy basin underwent mostly early Mesozoic normal slip and are reactivated Paleozoic thrusts. The adjacent basin has a much thicker section, transverse folds, and synthetic rider blocks. Contrasts in structural and stratigraphic styles are a response to local deformation controlled by reactivated fault zones of differing orientation under consistent northwest-southeast early Mesozoic extension rather than responses to a sequence of changing stress patterns.

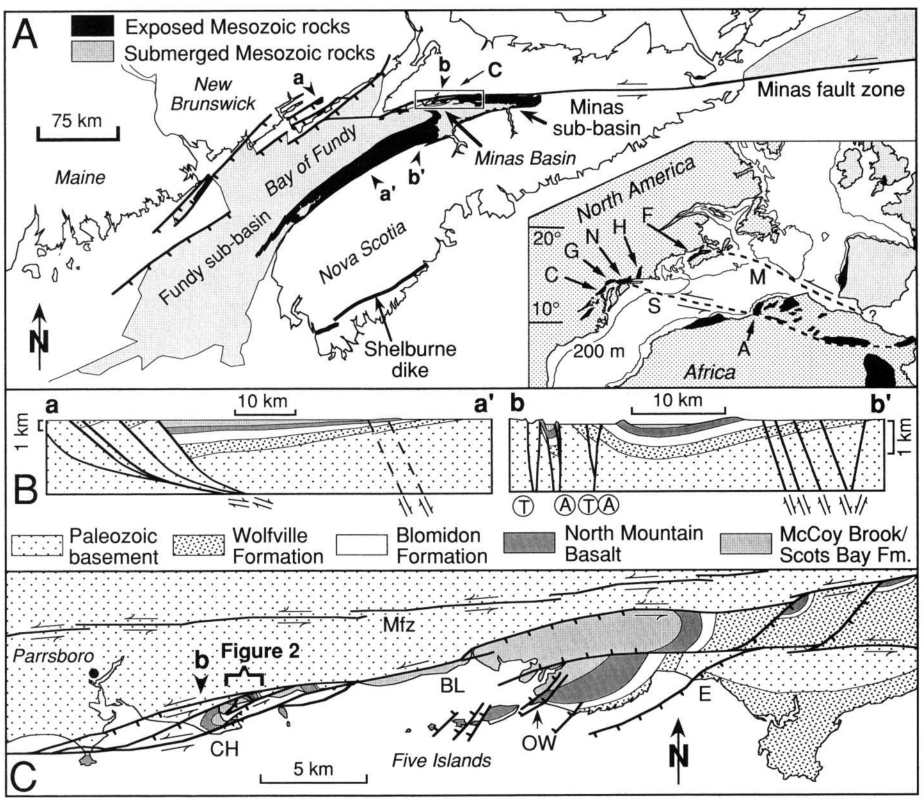

Figure 1. A: Fundy basin with locations of cross sections in B and of map in C. Inset shows exposed early Mesozoic basins in North America (C = Culpeper, F = Fundy, G = Gettysburg, H = Hartford, N = Newark), Iberia, and west Africa (A = Argana) and Minas fault zone–Gibraltar fracture zone (M) and South Atlas fault–Kelvin fracture zone (S) on predrift plate reconstruction (based on Masson and Miles, 1986; Ziegler, 1988). B: Cross sections of normal-faulted Fundy subbasin (a–a′) (based on Mobil seismic line BF-32) and transtensional Minas subbasin (b–b′). Note different scales for two cross sections. T indicates that fault-block motion was toward reader; A is away. C: Five Islands region on north side of transtensional Minas subbasin adjacent to Minas fault zone (Mfz), showing extensional strike-slip duplexes and position of maps and cross sections in Figure 2. BL = Blue Sac, CH = Clarke Head, E = Lower Economy, OW = Old Wife Point. Key to B applies to C. Base map adapted from Donohoe and Wallace (1982).

INTRODUCTION

The Triassic initiation of the breakup of Pangea was marked by the development of a long series of rift valleys, mostly half grabens, in North America, Europe, and Africa (Fig. 1A; Van Houten, 1977). In eastern North America these basins filled with thousands of metres of continental strata and tholeiitic igneous rocks termed the Newark Supergroup (Olsen, 1978). These basins show a complex, seemingly conflicting, array of fault orientations and slip directions (citations *in* Olsen et al., 1989). Suites of mostly normal and mostly strike-slip faults are interpreted in two fundamentally different ways. First, the different fault styles could be a consequence of a historical sequence of different regional stress fields (Sanders, 1963; Swanson, 1982; de Boer and Clifford, 1988). Second, a long period of consistent stress orientation may have reactivated a previously existing template of weak structures of variable orientation that controlled the distribution and orientation of younger features (Ratcliffe and Burton, 1985; Ratcliffe et al., 1986; Schlische and Olsen, 1988). Critical to testing these models is the timing of faulting relative to sedimentation. Here we show the first evidence for strike-slip motion, specifically during synrift sedimentation, in the Newark Supergroup. The east-striking Minas fault zone of the Fundy basin of Nova Scotia and New Brunswick was reactivated by left-oblique slip during the early Mesozoic. This strike-slip deformation was synchronous with the dip-slip deformation along the northeast-striking border faults and produced two distinct styles of synrift sedimentation and deformation within the same basin.

MINAS SUBBASIN

The Fundy basin consists of two subbasins of contrasting structural styles (Fig. 1): the northeast-trending Fundy subbasin—a large half graben—and the east-trending Minas subbasin. The Minas subbasin is located along the east-striking Minas fault zone, which marks the boundary between the Avalon and Meguma terranes (Keppie, 1982) and which underwent predominantly right slip through the Carboniferous (Keppie, 1982; Keppie and Dallmeyer, 1987; Mawer and White, 1987). During the northwest-southeast extension that formed the main half graben in the early Mesozoic, the fault zone was reactivated in many areas by left-oblique slip. The Minas subbasin is therefore a transtensional rift (in the sense of Harland, 1971).

The northern margin of the Minas subbasin consists of a complex series of synrift horsts, grabens, and half grabens in which the Triassic section is locally greatly condensed (Table 1). In the Five Islands area of Nova Scotia (Fig. 1C), splays of the Minas fault zone have a left-stepping relay geometry. Our geologic mapping indicates that extensional strike-slip duplexes (in the sense of Woodcock and Fischer, 1986) are present. Early Mesozoic rocks accumulated in troughs bounded by the northeast-striking normal and east-striking left-slip faults of the duplexes. Because strike-slip zones are complex features, there are some reverse faults, and an east-striking fault between Blue Sac and Lower Economy has an apparent dextral offset owing to the large amount of vertical separation (Fig. 1C).

Evidence for penecontemporaneous faulting and sedimention during left-oblique slip of the Minas fault zone is best exposed at Wasson Bluff (Fig. 2), east of Parrsboro (Fig. 1). Two well-exposed microbasins are developed on the faulted North Mountain Basalt and filled with basal McCoy Brook Formation, which consists of lacustrine, eolian, and minor fluvial units as well as basalt talus deposits. The talus deposits consist of angular clast-supported basalt breccias with a matrix of sandstone or mudstone (Tanner and Hubert, 1988). Consistent fine-scale layering defined by grain-size changes or basalt granules within the matrix indicate deposition of the matrix after accumulation of the adjacent basalt clasts. Much of the matrix contains abundant vertebrate fossils—the remains of prey of small carnivorous reptiles that lived among the voids between basalt clasts prior to the deposition of the matrix (Olsen et al., 1987). At all outcrops these talus slope deposits abut faults or basalt scarps and indicate scarp formation due to faulting during sedimentation.

The eastern microbasin is a 160 m by 50 m tilted graben bounded by a master fault (4 in Fig. 2) on the northeast, a transfer fault (3 in Fig. 2) on the west, and a series of antithetic faults forming domino-style blocks on the south (Fig. 2, cross section d-d′). The southeastern side of the basin is truncated by a normal fault. The southernmost domino is capped by a laterally extensive, variegated purple, fossil fish–bearing lacustrine mudstone, limestone, and basalt gravel. This unit, called the fish bed, is a key stratigraphic marker, tying this graben to the microbasin to the west. The northeastern border fault is at present a planar reverse fault, but could be a rotated normal fault in the fish-bed reference frame.

The western microbasin (Fig. 2, cross section c-c′) is a ~450-m-wide tilted half graben bounded on the north by east-striking left-lateral faults and on the northwest by a northeast-striking, predominantly dip-slip normal fault (1 in Fig. 2). Strata within this microbasin onlap North Mountain Basalt on the east, the wedge-shaped geometry of the basin is clearly visible in map view, and strata visible in outcrop thicken dramatically toward the normal fault (Fig. 2). The basin fill consists largely of eolian dune sand (Hubert and Mertz, 1984) underlain by the fish bed. Eolian sandstones abut >20-m-wide semi-allochthonous blocks of basalt near the normal fault (see Fig. 2). The presence of large, locally transported blocks of basalt, the preserved scarps and paleotalus cones, and the geometry of the microbasin fill show unequivocally that faulting, microbasin formation, and sedimentation were all coeval.

The entire section at Wasson Bluff is pervasively faulted at many scales. East-striking faults consistently show slickensides indicating left-lateral displacement with some dip-slip component (Fig. 2), regardless of their scale or inferred depth of burial. In one east-west fault (2 in Fig. 2), piercing points in zones of neptunian dikes in basalt show clear left-lateral and slightly oblique transport. North- or northeast-striking faults tend to show a much larger dip-slip component (Fig. 2). These faults thus mimic the pattern observed in the extensional strike-slip duplexes of the Five Islands region (Fig. 1C), which is consistent with northwest-southeast extension operating on an east-striking zone of weakness.

Clay-lined, curved surfaces with slickensides are common and locally pervasive in sandstones and mudstone-rich, basalt-bearing units. These mostly strike-slip and oblique slickensides resemble the hydroplastic slickensides that Laville and Petit (1984) described in clastic rocks of the early Mesozoic Argana basin of Morocco (Fig. 1A). Such structures probably formed under near-surface conditions in unlithified or only partly lithified sediments. Sandstones are also faulted on a small scale, the faults are not mineralized, and overall the deformational structures in the sedimentary rocks resemble those described by Beauchamp (1988) from the Moroccan High Atlas. Furthermore, reptile bones in the sandstones are commonly sheared. However, unfaulted, rounded and polished metamorphic pebbles, found among the ribs of one extensively faulted dinosaur skeleton and inferred to be gastroliths, indicate low confining pressures in incompetent rocks during faulting.

The North Mountain Basalt at Wasson Bluff contains abundant neptunian dikes of claystone, mudstone, and sandstone, 0.5 to 25 cm in width, some with clasts of basalt up to 5 cm wide. Dikes commonly follow columnar cooling joints, are most abundant close to faults, and are infilled fractures that opened in the basalt during extension under near-surface conditions. In most areas the widest and best-developed dikes formed along planes perpendicular to northwest-southeast regional extension (Fig. 2).

Active faulting during sedimentation is also indicated by dramatic changes in the thickness and coarseness of the Triassic Blomidon Formation. On the east side of Wasson Bluff, the Blomidon Formation consists of less than 10 m of conglomerate and sandstone. On the west side of Wasson Bluff, it is more than 40 m thick and is much finer grained. In fault blocks to the

TABLE 1. STRATIGRAPHY OF FUNDY BASIN

Units	Thickness* (m) M	F	C	Age	Description
McCoy Brook Formation	>200	0	357	Early Jurassic	Fluvial, deltaic, lacustrine, playa, and eolian clastic rocks; lacustrine limestones; and basalt agglomerates
Scots Bay Formation	0	<40	0	Early Jurassic	Lacustrine limestones and siltstones; chert; minor fluvial sandstone
North Mt. Basalt	100	270	333	Early Jurassic	Tholeiitic basalt flows
Blomidon Formation	10-180	200	1168	Late Triassic-Early Jurassic	Cyclic lacustrine, playa, sandflat, and deltaic clastic rocks; minor eolian sandstones and conglomerates
Wolfville Formation	0-300	300	>1708	MiddleTriassic-Late Triassic	Fluvial sandstones and conglomerates; eolian sandstones; minor deltaic-lacustrine deposits

*M, north shore of Minas Basin; F, southeast shore of Bay of Fundy; C, Chinampas well drilled near depocenter of Fundy sub-basin. After Olsen et al. (1989).

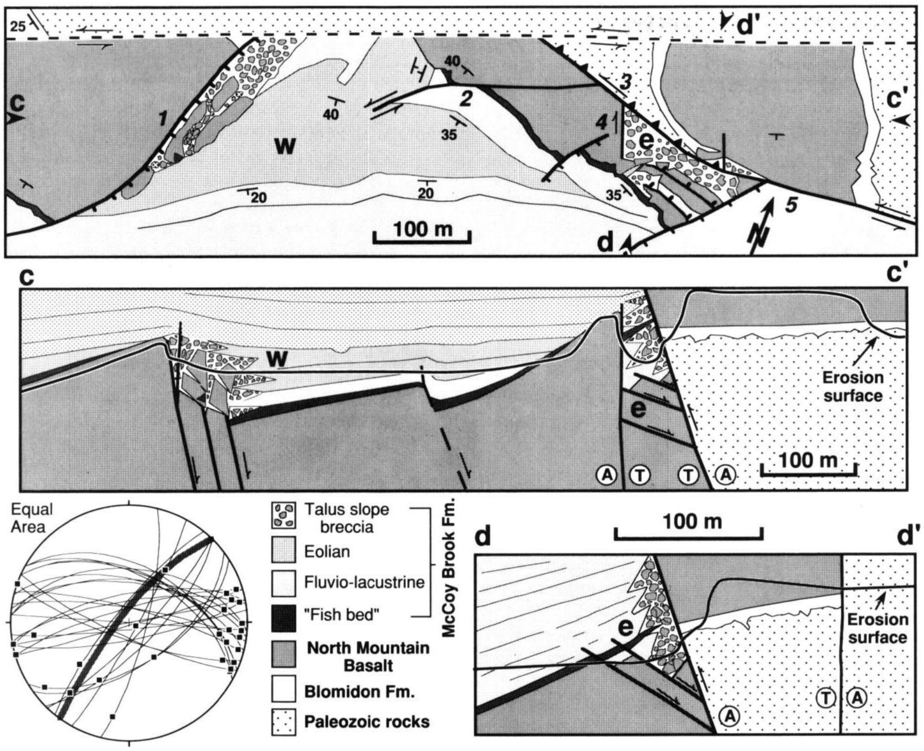

Figure 2. Wasson Bluff part of Five Islands region showing two syndepositional basins: e = eastern microbasin, w = western microbasin. Cross sections deviate from straight lines to encompass salient features. T is toward; A is away. Note in particular that eolian facies of McCoy Brook Formation thickens from 0 m in east to ~80 m adjacent to normal-fault boundary of western microbasin. Lower-hemisphere stereographic projection shows attitude of faults (thin great circles), slickenlines (boxes), and average orientation of neptunian dikes (shaded great circle) on west side of Wasson Bluff area, all consistent with northwest-southeast extension. Key faults are oriented (strike, dip, rake of slickenlines): 1: 019°, 84°SE, 90°; 2: 074°, 85°N, 12°E; 3: 290°, 70°–80°NE, ?; 4: 004°, 78°E, 20°S; 5: 069°–104°, 54°N–78°S, 5°–20°E. Neptunian dikes offset by fault 2 demonstrate unequivocal left-oblique slip, consistent with slickensides.

southwest (Clarke Head) and the southeast (Five Islands; Fig. 1C), the Blomidon is more than 150 m thick and even more fine grained. These variations show that the fault zone was active in the Wasson Bluff area during Triassic as well as Early Jurassic time.

The style of penecontemporaneous deformation and sedimentation seen at Wasson Bluff occurs at other areas along the Minas fault zone. Early Jurassic paleotalus slope deposits are present at Blue Sac and Five Islands (Fig. 1C; Olsen et al., 1989). At Lower Economy there is a small syndepositional basin of Middle Triassic age with exposed growth faults (Fig. 1C; Olsen et al., 1989); east-striking faults with predominantly left-oblique slip are prominent. Thus, largely left-oblique syndepositional faulting occurred over much of the length of the Minas fault zone for at least 30 m.y. (Middle Triassic–Early Jurassic).

FUNDY SUBBASIN

The northeast-trending Fundy subbasin is a large half graben with its depocenter below the Bay of Fundy (Fig. 1). On the basis of currently available seismic profiles, the northeast-striking border-fault system consists of 30°–50° southeast-dipping faults that slowly decrease in dip and merge with depth. Plint and van de Poll (1984), Keppie and Dallmeyer (1987), and D. Brown (1988, personal commun.) proposed that the border faults formed by the dip-slip reactivation of southeast-dipping Paleozoic thrust faults (Nance and Wagner, 1986) along the northwestern edge of the basin in response to a northwest-southeast extension direction, taken to be perpendicular to the strike of the Early Jurassic (Papezik and Baar, 1984) Shelburne dike in southern Nova Scotia (Fig. 1).

Seismic profiles and well logs show that 3–5 km of section are present in the depocenter of the Fundy subbasin, although exposed rider blocks along the western edge of the subbasin preserve only part of the Triassic Wolfville Formation and equivalents (see Nadon and Middleton, 1985) and less than 1 km of section is preserved in the Annapolis Valley along the hinge margin of the half graben (Table 1, Fig. 1). Thus, all units of early Mesozoic age thicken toward the border-fault system, indicating that the normal faults actively controlled Triassic through Early Jurassic sedimentation.

Gentle transverse folds (northwest-plunging axes) are present in the hanging walls of the border faults. Some are imaged in seismic profiles (e.g., Chevron BF-51), and one is exposed in the St. Martins, New Brunswick, area. Folds of this type are characteristic of the hanging walls adjacent to major north- to northeast-striking faults of most Newark Supergroup basins (Schlische and Olsen, 1988; Olsen et al., 1989).

DISCUSSION

The Fundy and Minas subbasins exhibit dramatically different styles of synrift deformation and sedimentation, even though they share the same stratigraphic units and formed synchronously. The Minas subbasin, developed along a high-angle left-oblique fault zone, consists of numerous nested sets of smaller syntectonic basins of considerable complexity, and contains greatly condensed stratigraphic sections. The Fundy subbasin developed along a predominantly dip-slip fault zone, the stratigraphic section is greatly thickened, and transverse folds and rider blocks are present. Because these two regions developed their differing styles synchronously over at least 30 m.y., the differences cannot be due to regionally shifting stress orientations during Late Triassic–Early Jurassic time, but must be due to local variations in stress regimes, most likely caused by the reactivation of major older structures of different orientations. Of course, on a longer time scale, the stress regime has changed since the Early Jurassic (e.g., Klitgord and Schouten, 1986; Manning and de Boer, 1989).

Major strike-slip faults, such as the Minas fault zone of North America and the South Atlas fault zone of Morocco (Fig. 1A), partitioned zones of shortening during the Paleozoic Appalachian, Variscan, and Hercynian orogenies (e.g., Arthaud and Matte, 1977). The South Atlas fault zone, like the Minas fault zone, was reactivated in a left-lateral sense during the early Mesozoic, and a comparable style of deformation and sedimentation developed in the adjacent basins of Morocco (Mattauer et al., 1972; Van Houten, 1977; Laville and Petit, 1984; Beauchamp, 1988). Similar structures also may be present in the narrow neck between the Newark and Gettysburg basins in Pennsylvania (Fig. 1A), where the east-striking border fault is aligned, in predrift position, with the South Atlas fault zone. The border fault of the narrow neck should have undergone left-oblique slip as a result of the northwest-southeast extension indicated by the average orientation of nearby Early Jurassic diabase dikes (Schlische and Olsen, 1988). Sinistral faults have been reported by Lucas et al. (1988). All of these left-lateral faults are not strike-slip faults in the sense of Anderson (1942), but are transfer faults (or crustal transform faults) that formed during extension and linked dip-slip fault zones. The simultaneous development of normal faults and associated half grabens bears this out. Similar arrangements of strike-slip and normal faults are common in extensional provinces (e.g., Gibbs, 1984; Rosendahl, 1987).

In the Newark, Hartford, Gettysburg, and Culpeper basins (Fig. 1A), northwest-southeast extension produced wedge-shaped half grabens and predominantly dip-slip movement on the main reactivated north- to northeast-striking border faults. In the hanging walls of these faults are well-exposed folds oriented perpendicular to the associated faults, similar to those in the Fundy subbasin. The folds do not extend into the footwall or fold the faults, and they die out away from the fault in the hanging wall. The folds are spatially and causally related to the faults responsible for basin subsidence and, on the basis of outcrop study, formed during and after sedimentation (Schlische and Olsen, 1988; Olsen et al., 1989). These dip-slip–related folds involve strata ranging in age from Late Triassic to Early Jurassic and thus formed at the same time as the strike-slip– and dip-slip–related structures in the Fundy basin (Olsen et al., 1989).

We explain the complex structural styles seen in Newark Supergroup basins without resort to a particular historical sequence of changing stress regimes. Similar suites of penecontemporaneous structures and sedimentary deposits should be present in other extensional basins of the world in which both dip-slip and strike-slip margins exist.

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