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# The Ins and Outs of Buttress Folds: Examples from the Inverted Fundy Rift Basin, Nova Scotia and New Brunswick, Canada

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## ABSTRACT

Buttress folds form in the hanging walls of non-planar normal faults during basin inversion. Slip occurs more easily along the lower, more gently dipping fault segments, whereas the upper, more steeply dipping fault segments act as buttresses, inhibiting slip and causing the hanging-wall strata to shorten and fold. We have examined the geometry of buttress folds in the inverted Fundy rift basin, Canada, using seismic (both offshore and onshore), field, aeromagnetic, and DEM data. Generally, the hinges of the buttress folds in the Fundy rift basin parallel the strikes of the adjacent extensional fault zones. The tightest folds occur adjacent to the more steeply dipping, upper fault segments, whereas broader folds occur adjacent to the more gently dipping, upper fault segments. The folds commonly occur as trains of hanging-wall synclines and anticlines, indicating that a detachment level exists at depth. Therefore, many of the buttress folds in the Fundy basin are combinations of buttress and detachment (buckle) folds. Most natural examples of buttress folds, and those produced in analogue models, consist of a single hanging-wall anticline adjacent to the fault zone. The combination buttress/detachment folds in the Fundy rift basin, however, consist of either a syncline or an anticline adjacent to the fault zone.

Based on kinematically compatible slip vectors on differently oriented segments of the border-fault system, the relative displacement direction of hanging-wall blocks to footwall blocks during inversion of the Fundy rift basin was northeast-southwest. This inversion-related deformation is, at least partially, partitioned into pure-shear and simple-shear components. The fault-parallel buttress/detachment folds accommodate the pure-shear component, whereas fault-parallel, left-lateral strike-slip faults accommodate the simple-shear component. Thus, the buttress/detachment folds in the Fundy basin do not necessarily indicate the relative displacement direction of hanging-wall blocks to footwall blocks. Instead, their trends reflect the variable local shortening direction associated with the pure-shear component of the deformation.

## Introduction

Buttress folds form in the hanging walls of non-planar normal faults during basin inversion (*e.g.*, Dart *et al.*, 1995; McClay, 1995). Slip occurs more easily along lower, more gently dipping fault segments; however, upper, more steeply dipping fault segments act as a buttress, thereby inhibiting slip and causing the hanging-wall strata to shorten and fold (Fig. 1A). Most geologic examples of buttress folds, as well as those produced in experimental (analogue) models, have a single hanging-wall anticline whose axis parallels the border-fault system (*e.g.*, Dart *et al.*, 1995; Eisenstadt and Withjack, 1995; McClay, 1995; Baum, 2006) (Figs. 1Aiii and 1B). How representative are these examples of buttress folds? Do all buttress folds have anticlinal geometries? How do the trends of the axes of buttress folds relate to the regional shortening direction?

We have used geological and geophysical data from the inverted Fundy rift basin, Nova Scotia and New Brunswick, Canada (Fig. 2), to address these questions. Specifically, we have reinterpreted 2D seismic-reflection data from the Bay of Fundy, including several key reprocessed seismic lines. We have also: 1) interpreted new seismic data from onshore Nova Scotia; 2) mapped, in detail, cliff and tidal-flats outcrops from onshore Nova Scotia; 3) incorporated high-resolution, digital elevation model data (Nova Scotia Department of Natural Resources, 2004; Canadian Council on Geomatics, 2008) and aeromagnetic data (King, 2005a, 2005b; Oneschuk and Dumont, 2005a, 2005b) from the Bay of Fundy region; and 4) compared the structures in the Fundy rift basin to those in scaled experimental models of inversion (orthogonal and oblique) (Baum, 2006).

### **Geometries of Faults and Folds**

The Fundy rift basin is the northernmost exposed basin in the eastern North American Mesozoic rift system that formed during the fragmentation of Pangea (Fig. 2A). It has three distinct structural constituents: the Chignecto, Fundy, and Minas subbasins (Olsen and Schlische, 1990; Figs. 2B and 2C). The offshore and onshore seismic data show that the border-fault system of the Fundy rift basin is complex, consisting of linked northeast- and east-striking fault zones (Fig. 2C). The Chignecto and Fundy subbasins are bounded on the northwest by the northeast-striking Chignecto and Fundy border-fault zones, respectively. The Fundy and Minas subbasins are bounded on the north by the east-striking Cobequid/Chedabucto border-fault zone (*e.g.*, Olsen and Schlische, 1990; Withjack et al., 1995). All fault zones have gentle dips at depth, whereas the east-striking Cobequid/Chedabucto fault zone has steep dips at shallow levels (Fig. 3).

Folds are present in the hanging wall of the entire linked border-fault system of the Fundy rift basin (Fig. 2C). An absence of growth beds indicates that most of this folding occurred after rifting during a subsequent shortening/inversion event. Most of these inversion-related folds are subparallel to the adjacent fault zone (Fig. 2C). Thus, the trends of the fault-parallel folds vary, reflecting the trends of the adjacent fault zones. Generally, broad anticlines develop in the hanging wall of the northeast-striking Fundy fault zone (Fig. 3G), whereas a train of anticlines and synclines develops in the hanging wall of the east-striking Cobequid/Chedabucto fault zone (Fig. 2C). The tightest and narrowest folds occur adjacent to the most steeply dipping, upper segments of the Cobequid/Chedabucto fault zone (Figs. 3C and 3D). Hanging-wall anticlines (*e.g.*, Fig. 3D) and synclines (*e.g.*, Fig. 3C) occur directly adjacent to the east-striking Cobequid/Chedabucto fault zone.

Based on these characteristics, we propose that the fault-parallel, hanging-wall folds in the Fundy rift basin are, at least in part, buttress folds. The onshore seismic data show that the train of folds in the hanging wall of the east-striking Cobequid/Chedabucto fault zone does not affect the gently dipping, lower segment of the fault zone, indicating that a detachment exists between the base of the synrift section and the border-fault surface (Fig. 3A). Considering the limited distance between the base of the synrift section and the border-fault surface, the most likely detachment is the border-fault surface itself. Other potential detachment levels include pre-existing, low-angle Paleozoic thrust faults and evaporite units in the prerift section (*e.g.*, Waldron and Rygel, 2005). Thus, many of the fault-parallel folds in the hanging wall of the east-striking Cobequid/Chedabucto fault zone are actually a combination of buttress and detachment (buckle) folds. These combination buttress/detachment folds differ from traditional anticlinal buttress folds in that multiple folds develop and either an anticline or a syncline is present directly adjacent to the fault zone (Figs. 1Aiii and iv).

To define the small-scale structures associated with the buttress/detachment folding, we have mapped, in detail, several field sites within the east-striking Cobequid/Chedabucto fault zone (Figs. 2C, 4, 5). The small-scale deformation at these field sites consists predominantly of east- to northeast-striking, steeply dipping, left-lateral strike-slip faults (based on slickensided fault surfaces) and minor post-depositional folds. The faults cut and/or bound the minor post-

depositional folds (Fig 4). Thus, the small-scale, left-lateral strike-slip faults are also post-depositional structures.

### **Displacement Directions and Strain Partitioning**

Scaled experimental (analogue) models of oblique rift-basin inversion show that the trends of the axes of buttress folds are parallel to the trends of the adjacent fault zones, regardless of the displacement direction of the hanging wall relative to the footwall (Baum, 2006). Thus, the models suggest that the deformation produced by oblique inversion is at least partially partitioned into fault-perpendicular and fault-parallel components. As mentioned previously, the linked border-fault system of the Fundy rift basin has fault zones with two trends: the northeast-striking Fundy fault zone and the east-striking Cobequid/Chedabucto fault zone (Fig. 2). Therefore, the presence of fault-parallel buttress/detachment folds in the hanging walls of both fault zones indicates a component of fault-perpendicular shortening along both margins and, thus, restricts the displacement direction of the hanging wall relative to the footwall of the linked border-fault system during inversion (Figs. 5i and 5ii). Specifically, the relative displacement direction could range from northeast to west during inversion (Fig. 5Aiii). The abundance of small-scale, east- to northeast-striking, left-lateral strike-slip faults at the field sites within the east-striking Cobequid/Chedabucto fault zone suggests a fault-parallel component of left-lateral shear and further restricts the displacement direction of the hanging wall relative to the footwall of the linked border-fault system during inversion. Specifically, the relative displacement direction must have had an eastward component during inversion. Together, the fault-parallel buttress/detachment folds and the east- to northeast-striking, left-lateral strike-slip faults indicate that the hanging wall of the linked border-fault system of the Fundy rift basin moved northeast relative to its footwall during inversion (Fig. 5iv).

The seismic and field data show that the postrift deformation in the inverted Fundy rift basin is, at least partially, partitioned into a pure-shear component and a simple-shear component (*e.g.*, Sanderson and Marchini, 1984; Jones and Tanner, 1995). The fault-parallel, buttress/detachment folds accommodated the pure-shear component, whereas the left-lateral strike-slip faults accommodated the simple-shear component (Figs. 5B and 5C). The strain partitioning in the inverted Fundy rift basin is similar to strain partitioning observed in other transpressional zones (Jones and Tanner, 1995).

### **Summary and Conclusions**

Two distinct deformation styles developed during inversion of the Fundy rift basin: 1) high-angle, left-lateral strike-slip faults that are subparallel to the border-fault zones, and 2) buttress and combination buttress/detachment folds whose axes are subparallel to the border-fault zones. Thus, the inversion-related deformation in the Fundy rift basin is, at least partially, partitioned into simple-shear (*i.e.*, strike-slip faulting) and pure-shear (*i.e.*, buttress/detachment folding) components. The tightest and narrowest buttress/detachment folds occur adjacent to the most steeply dipping, upper segments of the border-fault zones. Most natural examples of buttress folds, and those produced in analogue models, consist of a single hanging-wall anticline. The combination buttress/detachment folds in the inverted Fundy rift basin, however, consist of trains of folds, with either a syncline or an anticline adjacent to the border-fault zone. The geometries of these buttress/detachment folds reflect the local, fault-perpendicular shortening direction associated with the pure-shear component of deformation; therefore, they are biased indicators of the displacement direction of the hanging wall relative to the footwall. However, their occurrence along two border-fault zones with different trends, combined with the presence of left-lateral strike-slip faults subparallel to the border-fault zones, constrains the relative displacement direction of the hanging wall to the footwall to the northeast.

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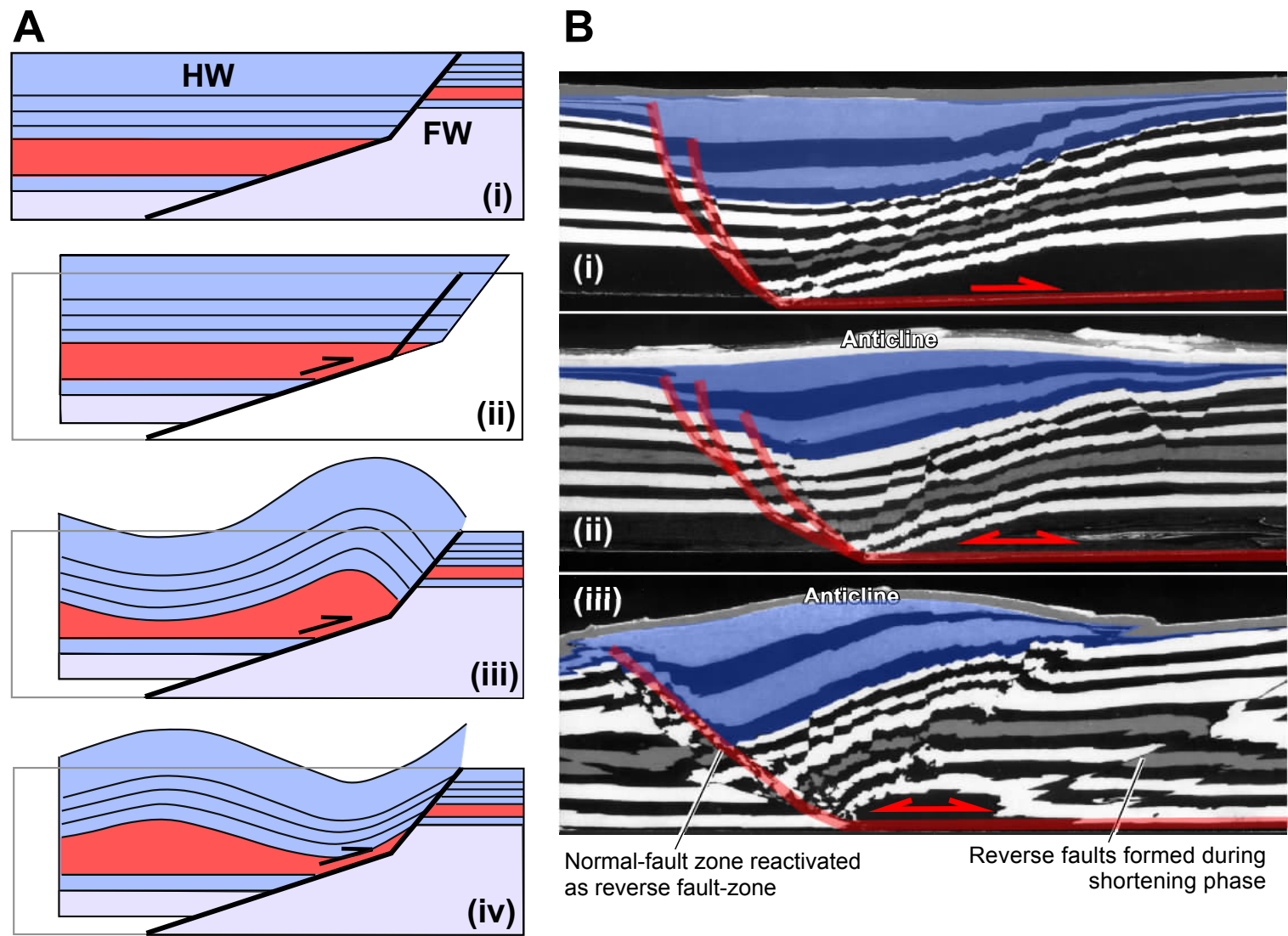
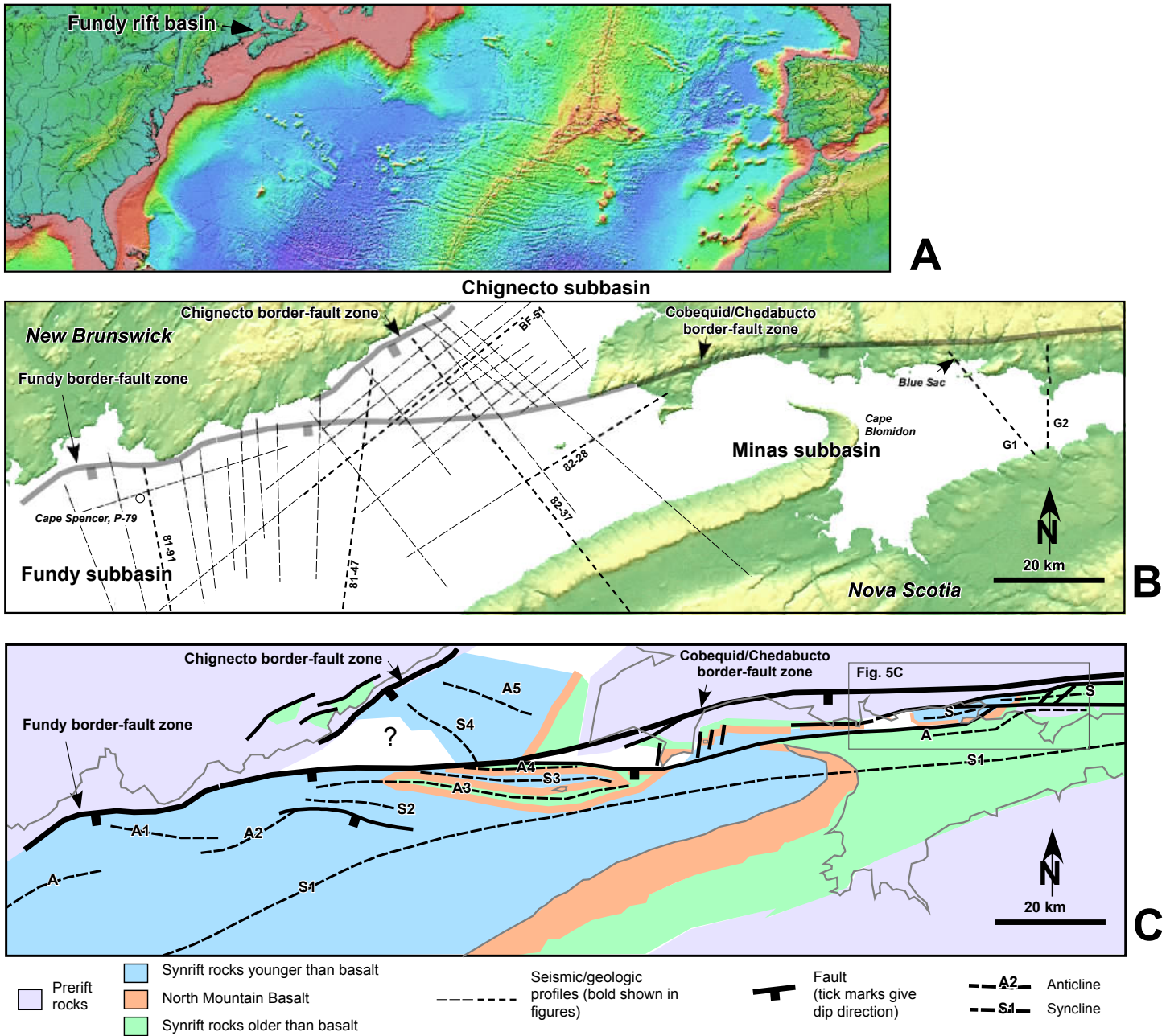


Figure 1. A. Development of buttress folds. (i) Geometry prior to folding showing pre-existing normal fault whose dip decreases with depth. Generally, footwall is stronger than hanging wall because footwall has thinner sedimentary cover above strong crystalline basement. (ii) Reverse slip would create space problem (overlap) at shallow depths. In response to space problem, folds form in hanging wall. The fold adjacent to the fault may be an anticline (iii) or a syncline (iv). The cross sections are line-length balanced, and the ductile unit (red) is area-balanced. B. Experimental models of inversion-related buttress folds (modified from Eisenstadt and Withjack, 1995). (i) After extension. (ii) After extension and mild inversion. (iii) After extension and severe inversion. The red lines are major faults that formed during extension. The anticline in (ii) and (iii) is a buttress fold.



**Figure 2.** A. Topographic map of Atlantic Ocean and conjugate continental margins: [http://topex.ucsd.edu/marine\\_topo/gif\\_topo\\_track/topo8.gif](http://topex.ucsd.edu/marine_topo/gif_topo_track/topo8.gif). B. Map of northern Fundy rift basin showing junction of three structural subbasins (Fundy, Minas, and Chignecto subbasins), geographic features, major faults, seismic coverage, locations of cross sections (G1 and G2), and field sites. Shaded-relief map based on data from Canadian Council on Geomatics (2008). C. Geologic map of northern Fundy rift basin based on seismic data, outcrop and well data (Withjack et al., 1995), seafloor topography and subcrop information (Swift and Lyall, 1968), and aeromagnetic data (King, 2005a, 2005b; Oneschuk and Dumont, 2005a, 2005b).

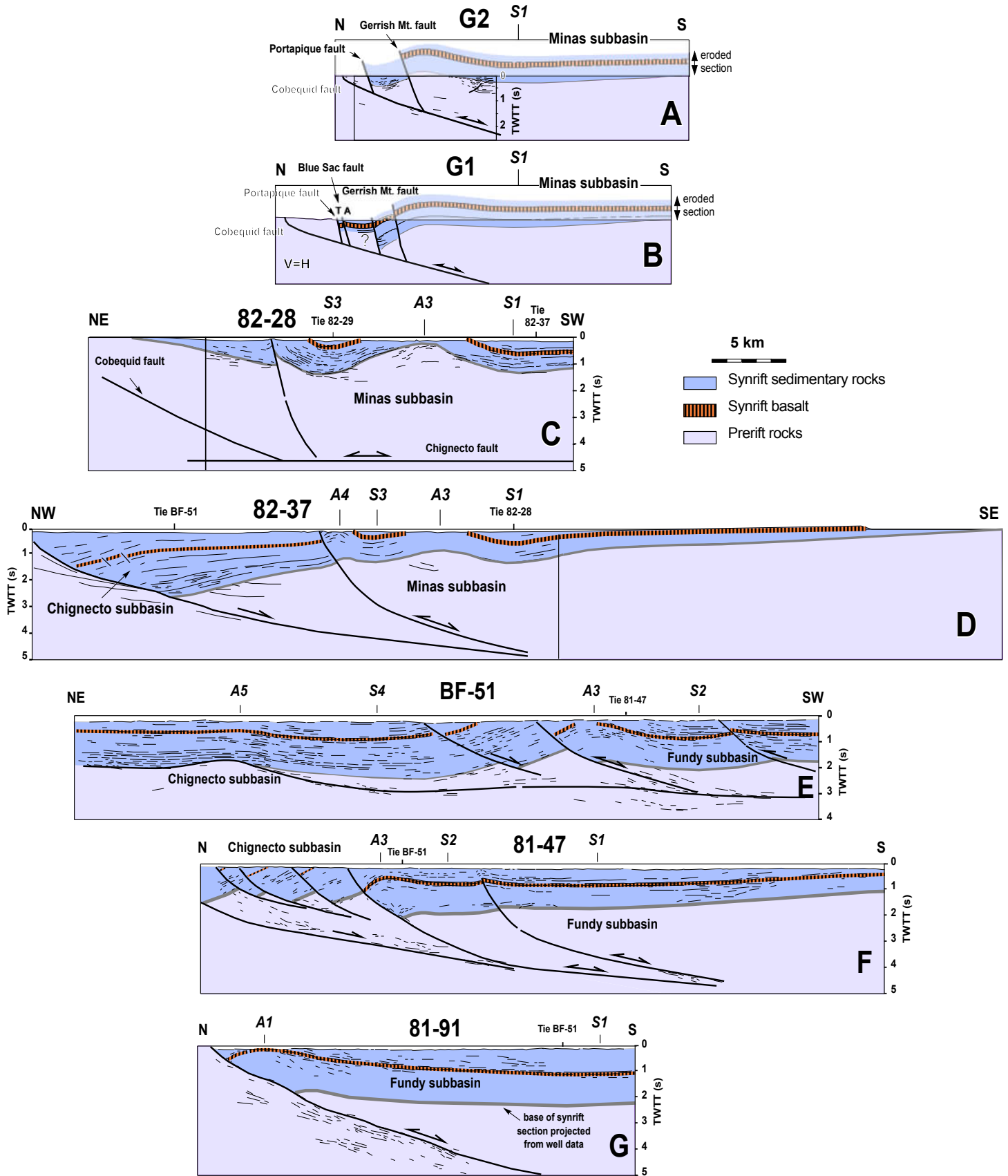
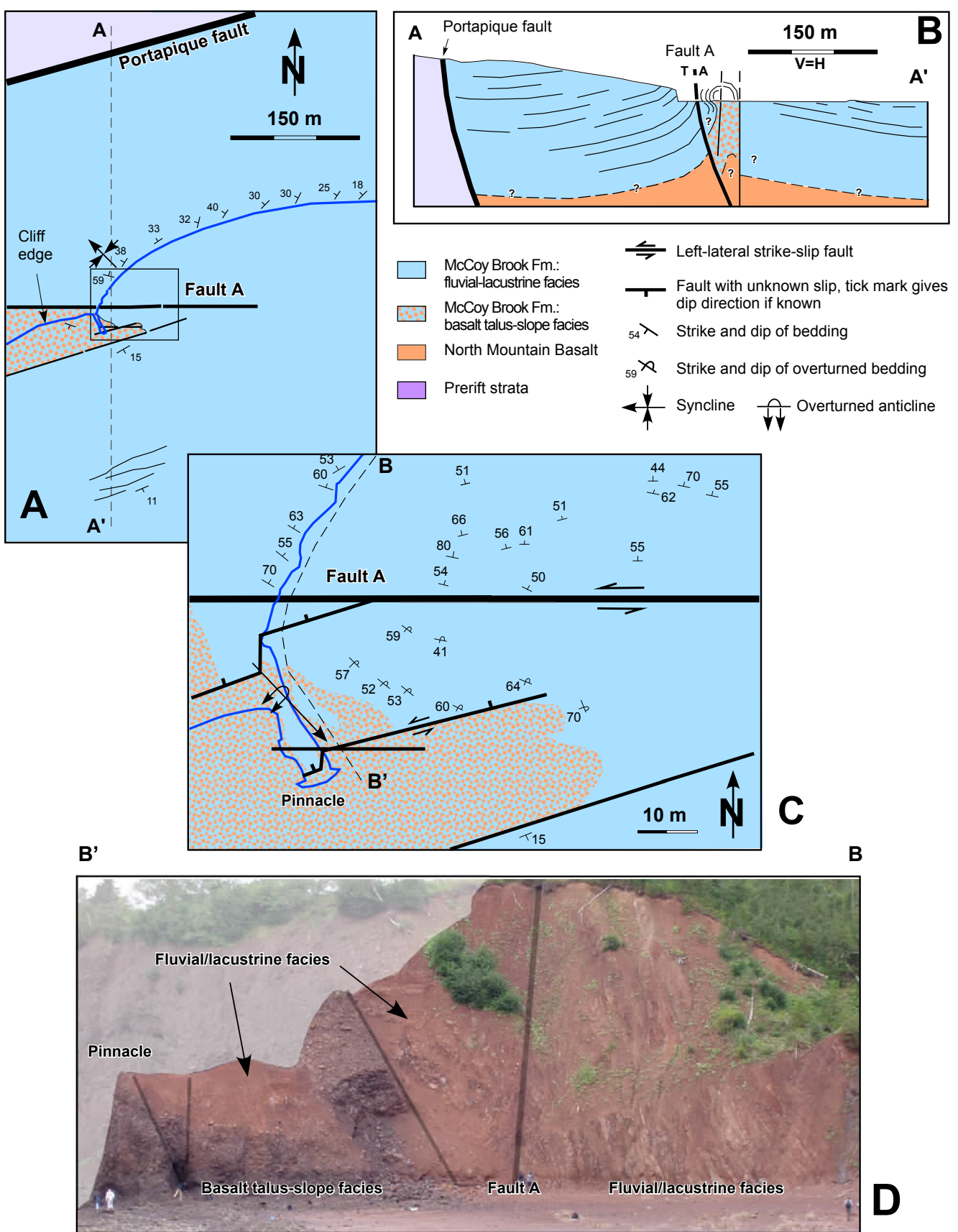
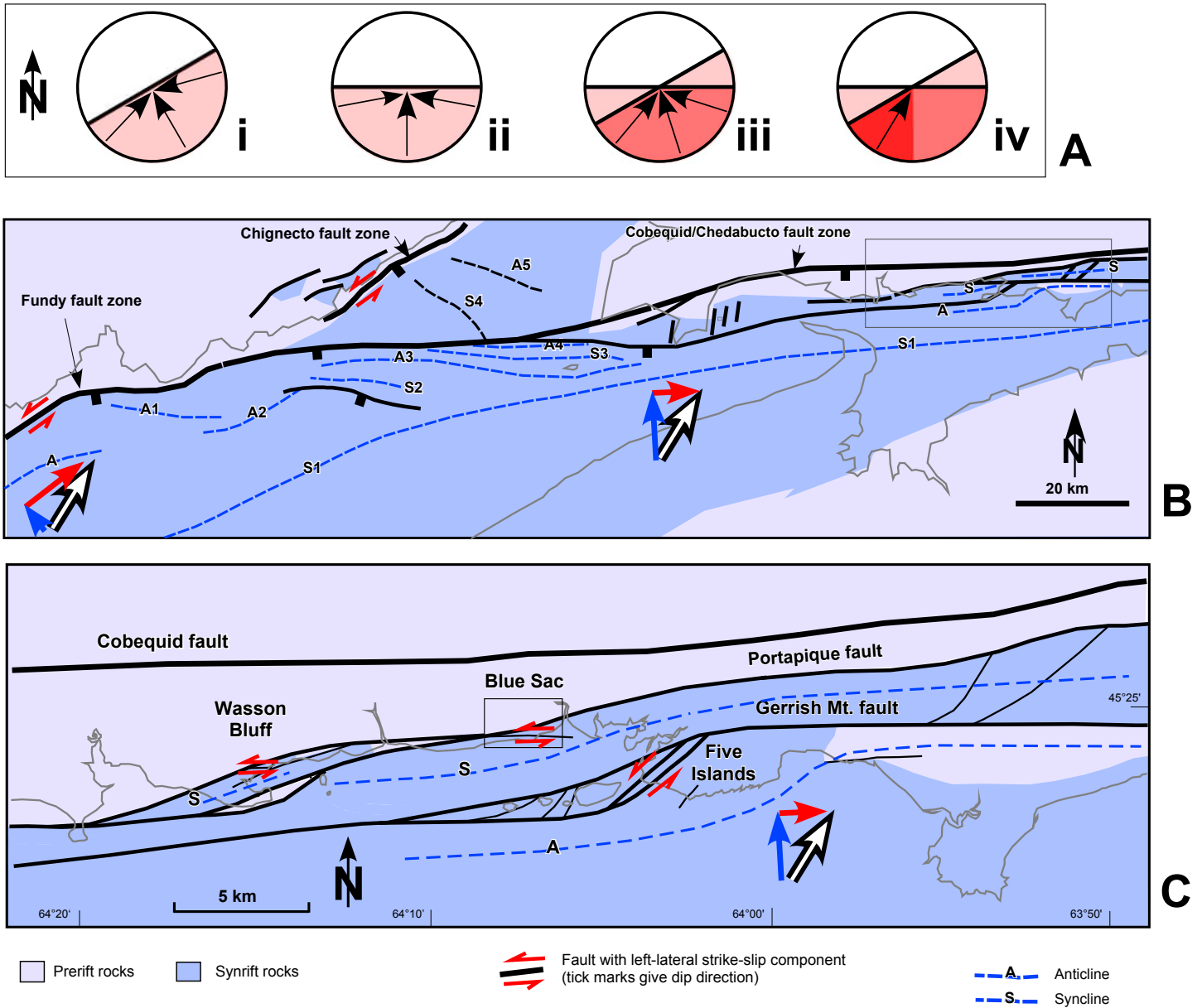


Figure 3. Sections across Fundy basin based on field, well, and seismic data. See Figure 2 for locations. Boxed portions are interpreted line drawings of seismic profiles, displayed at approximately 1:1 assuming an average velocity of 3.5 km/s. (A) Cross section G2 based in part on onshore seismic data. Contacts in center of basin are projected from Cape Blomidon (see Fig. 2 for location). (B) Cross section G1, based in part on work by Donohoe and Wallace (1982). Contacts in center of basin are projected from Cape Blomidon (see Fig. 2 for location). (C) Northeastern portion of seismic line 82-28 and onshore continuation. (D) Seismic line 82-37 and onshore continuation. (E) Seismic line BF-51. (F) Seismic line 81-47. (G) Seismic line 81-91. Arrows show components of fault slip in plane of cross section. A and S indicate anticlines and synclines shown in Figure 2C.



**Figure 4: Geology of the Blue Sac area.** A) Simplified geologic map showing faults and distribution of facies in the McCoy Brook Formation. Bedding on north side of Fault A steepens and rotates counterclockwise with increasing proximity to fault. B) Geologic cross section A-A' [location shown in (A)], showing overturned anticline. C) Detailed geologic map of boxed area in (A). Fault A strikes due east, dips steeply to the south, and has shallow southwest-raking slickenlines. Minor faults show left-lateral separation and subhorizontal slickenlines. Anticline has overturned NE limb. D) Photo of north-south trending cliff face from pinnacle to north of Fault A viewed toward the west. Geologists for scale.



**Figure 5.** (A) Displacement direction of hanging wall relative to footwall of linked border-fault system of Fundy rift basin during inversion. (i) Possible range of relative displacement directions based on presence of buttress folds in hanging wall of northeast-striking Fundy fault zone. (ii) Possible range of relative displacement directions based on presence of buttress/detachment folds in hanging wall of east-striking Cobequid/Chedabucto fault zone. (iii) Possible range of relative displacement directions combining information from i and ii. (iv) Possible range of relative displacement directions combining information from i and ii and considering presence of east-striking, left-lateral strike-slip faults observed at field sites. Regional (B) and local (C) maps of northern Fundy rift basin. White arrows with black borders show displacement direction of hanging wall relative to footwall of linked border-fault system during inversion. The northeast-striking fault zones underwent highly oblique inversion, whereas the east-striking fault zones underwent oblique inversion. Blue arrows show pure-shear component and resultant fault-parallel, buttress/detachment folding, and red arrows show simple-shear component and resultant east-striking faults with left-lateral strike-slip components. Many faults have a significant reverse-slip component as well as the left-lateral strike-slip component.