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Mid-continent tectonic inversions, Northwest Territories, Canada*

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Abstract—Four types of tectonic inversion are recorded on reflection seismic data from the area northwest of Great Bear Lake in the Northwest Territories, Canada. The strata involved span about 1.7 Ga of Proterozoic and Phanerozoic history, and have been subjected to at least five tectonic events, two extensional, two compressional and one transpressional. Two types of positive inversion, one type of negative inversion, and one type of double inversion (positive following negative) are documented. One of the positive inversions is atypical in that it involves no reversal in tectonic polarity; it was effected by a renewal of compression. During the entire 1.7 Ga time span the successive tectonic phases occurred in a mid-continental setting far from any known active plate margin(s). Copyright © 1996 Published by Elsevier Science Ltd

INTRODUCTION

Proterozoic and Phanerozoic strata recorded on reflection seismic records from the region northwest of Great Bear Lake, Northwest Territories, Canada (Figs. 1 and 2) are about 15 km thick and appear to represent about 1.7 Ga, based on tentative correlations with strata on Coppermine Homocline to the east. During that prolonged history the strata were subjected to a variety of extensional, compressional and transpressional events, with a strong tendency for reactivation of earlier structures. All tectonic phases affected strata in a mid-continent setting far from any known active plate margin. Among the various reactivations, this paper focuses on tectonic inversions of which all but one were caused by a reversal in stress field polarity. A variety of inversion styles occurs, as follows:

- Classical positive inversions (Fig. 3) wherein extensional half-grabens were inverted as compressional or transpressional uplifts.
- Negative inversions wherein thrust fault uplifts were inverted as half-grabens.
- Negative/positive double inversions wherein negative-inversion half-grabens were in turn partially inverted as faulted anticlines due to transpressional reactivation of the master fault.
- Positive inversion wherein a compressional syncline was inverted as a compressional anticline. This atypical inversion did not require a reversal in polarity of the regional stress field.

Inversion tectonics definition

In the published report of discussions (Cooper *et al.* 1989) which followed the Inversion Tectonics Meeting held at the Royal Society on 3–4 March 1987, Cooper & Williams (1989, p. 346) suggest 'requirements for inversion' that would essentially restrict the term to classical half-graben inversions such as illustrated in Fig. 3, although they did accept the concept of 'negative' inversions where compression and uplift were followed by extension and basin formation. The term 'inversion' would require stress inversion as well as basin inversion, and they proposed specific exclusion of situations where basins, formed under compression, were subsequently inverted by further compression. Elsewhere in the discussions, however, Stoneley (1989, p. 340), and Todd & Turner (1989, p. 340) argued that 'inversions' should include basins formed from compression which passed through a transition from subsidence to uplift without a significant change in the regional stress regime. We include an example, here, of a compressional basin inverted by subsequent compression and thus find the definition of Cooper & Williams too restrictive. Ziegler (1989) suggested that authors should specify in a few words what, in their usage, the term 'inversion' means. Accordingly, we return to the earlier, descriptive and non-genetic definition of Glennie & Boegner (1981):

> "Structural inversion . . . involves conversion of a basin area into a structural high. The converse is also possible so that inversion can be considered in both positive (uplift) and negative (subsidence) senses relative to the immediately preceding history" [quotation taken from Cooper *et al.* 1989, p. 345].

TECTONIC AND STRATIGRAPHIC FRAMEWORK

In the region northwest of Great Bear Lake in northwestern Canada (Fig. 1), about 1500 m of Lower Cambrian and younger Phanerozoic strata unconformably overlie more than 13.5 km of Proterozoic strata. The gently angular sub-Cambrian unconformity is obvious on most seismic sections. The Proterozoic section can be subdivided into four major unconformity-bounded assemblages which we correlate (Cook & MacLean

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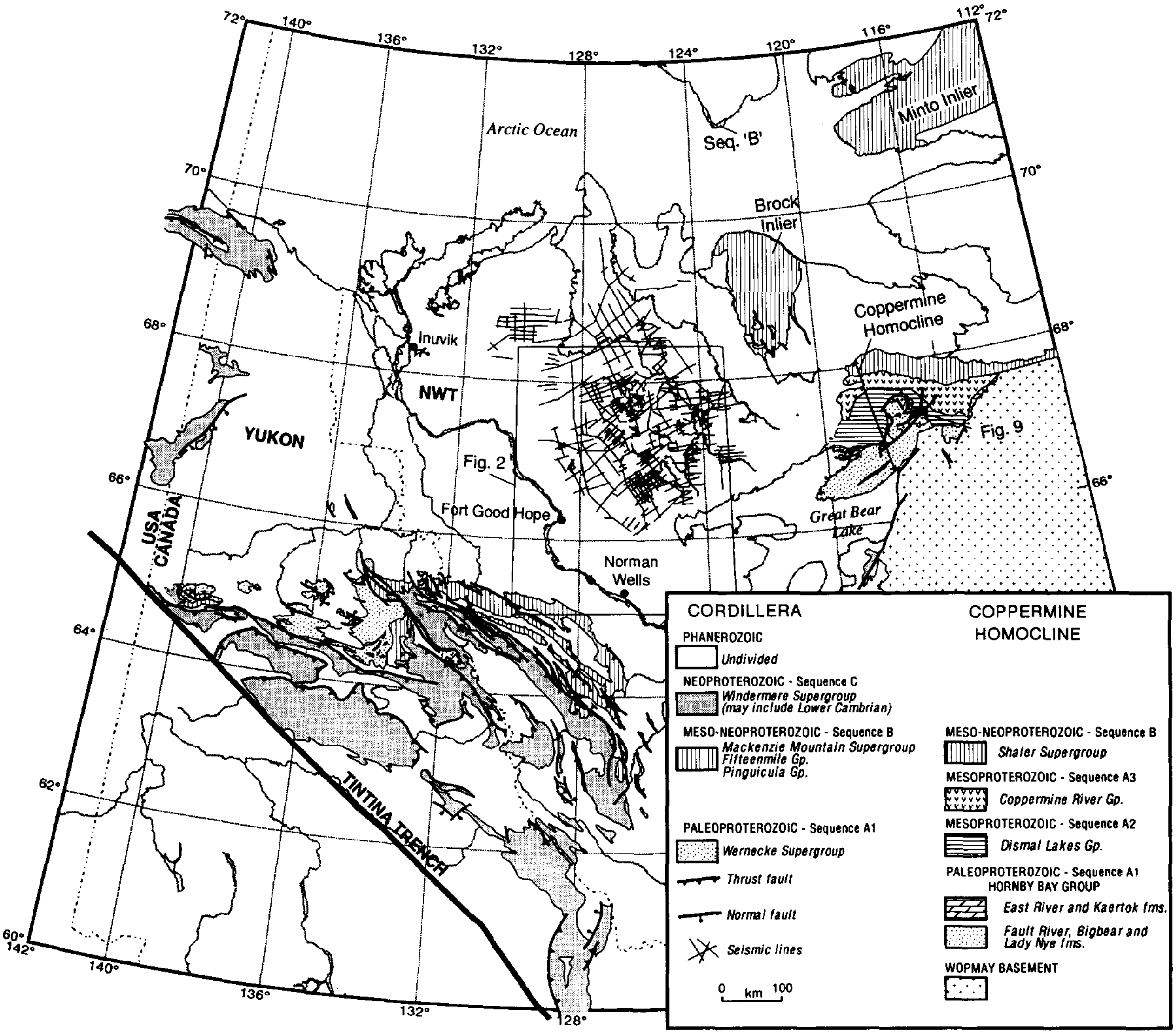

Fig. 1. Location map showing seismic data control, regional distribution of Proterozoic sequences, and location of Figs. 2 and 9.

1992, 1995, MacLean & Cook 1992) with outcropping Proterozoic strata mapped by Ross & Kerans (1989) on Coppermine Homocline to the east. Our correlation scheme (Fig. 4) is based on a variety of stratigraphic, structural and geochemical similarities. Important components of our correlation rationale are summarized as follows. Precambrian basalts drilled in the subsurface are considered to correlate with the Coppermine basalts on Coppermine Homocline (Sevigny *et al.* 1991). A regional unconformity, underlying the Dismal Lakes Assemblage in the subsurface, is considered to be equivalent to a mapped unconformity at the base of the Dismal Lakes Group on the homocline. Pre-unconformity compression and post-unconformity extension affected both subsurface and surface strata. Hornby Bay Assemblage, underlying the subsurface unconformity, is subdivided into three seismic units which appear to correspond to three lithostratigraphic units of the Hornby Bay Group exposed on the homocline. This outline is expanded somewhat in the following paragraphs, and a detailed discussion of correlations is presented elsewhere (Cook & MacLean 1995).

In the subsurface, seismic basement is considered to represent crystalline basement. The study area (Fig. 1) is flanked to the east by the northward-trending Great Bear Magmatic Zone of the 1.84–1.9 Ga Wopmay orogen (Hoffman & Bowring 1984) and to the southwest by the arcuate N- to NW-trending Fort Simpson magnetic anomaly where granites, sampled by two wells some 700 km south of the study area, have U–Pb dates of 1845 Ma (Villeneuve *et al.* 1991). The intervening belt, which includes our study area, was assigned by Ross (1991) to the Hottah Terrane with an age of 1.85–2.38 Ga. In the eastern part of the study area, basement is overlain by an unnamed, layered unit, up to 3 km thick (see Fig. 6), which has no apparent counterpart on Coppermine Homocline. Over the rest of the study area, basement is overlain by a tripartite assemblage (Hornby Bay Assemblage) which we correlate with the Hornby Bay Group on the homocline. This assemblage comprises a lower Basinal Unit (3–6 km thick, seismically dull), a middle Platformal Unit (600–1100 m thick, seismically layered) and an upper discontinuous Syntectonic Unit (up to 4.5 km thick, variably layered). These

Fig. 2. Location map showing seismic line locations for Figs. 5, 6, 7, 8 and 10. Geology from Yorath & Cook (1981).

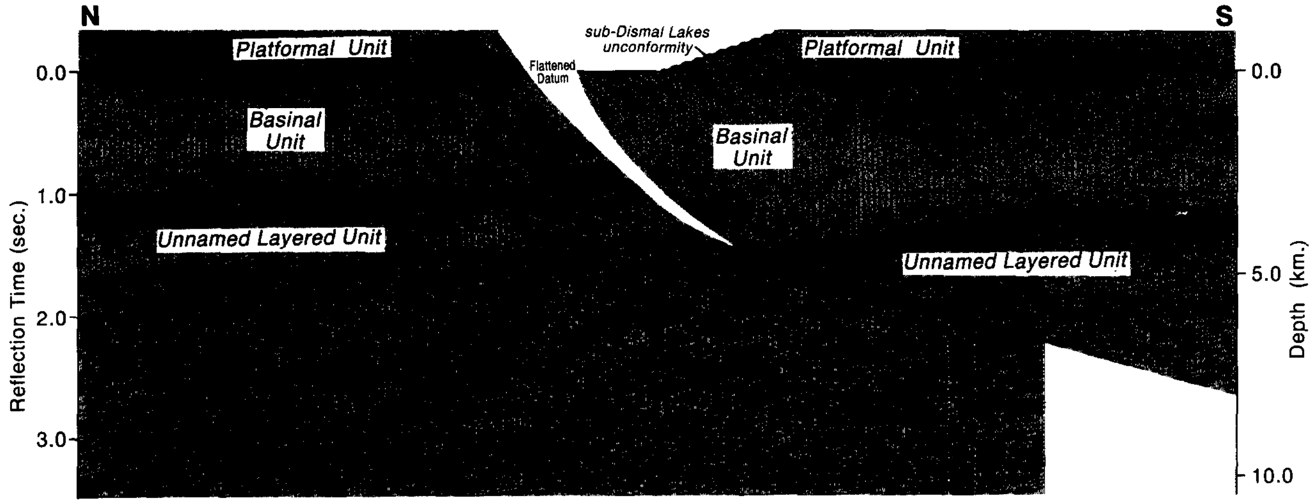

Fig. 6. (c) *For rest of figure and caption, see facing page.*

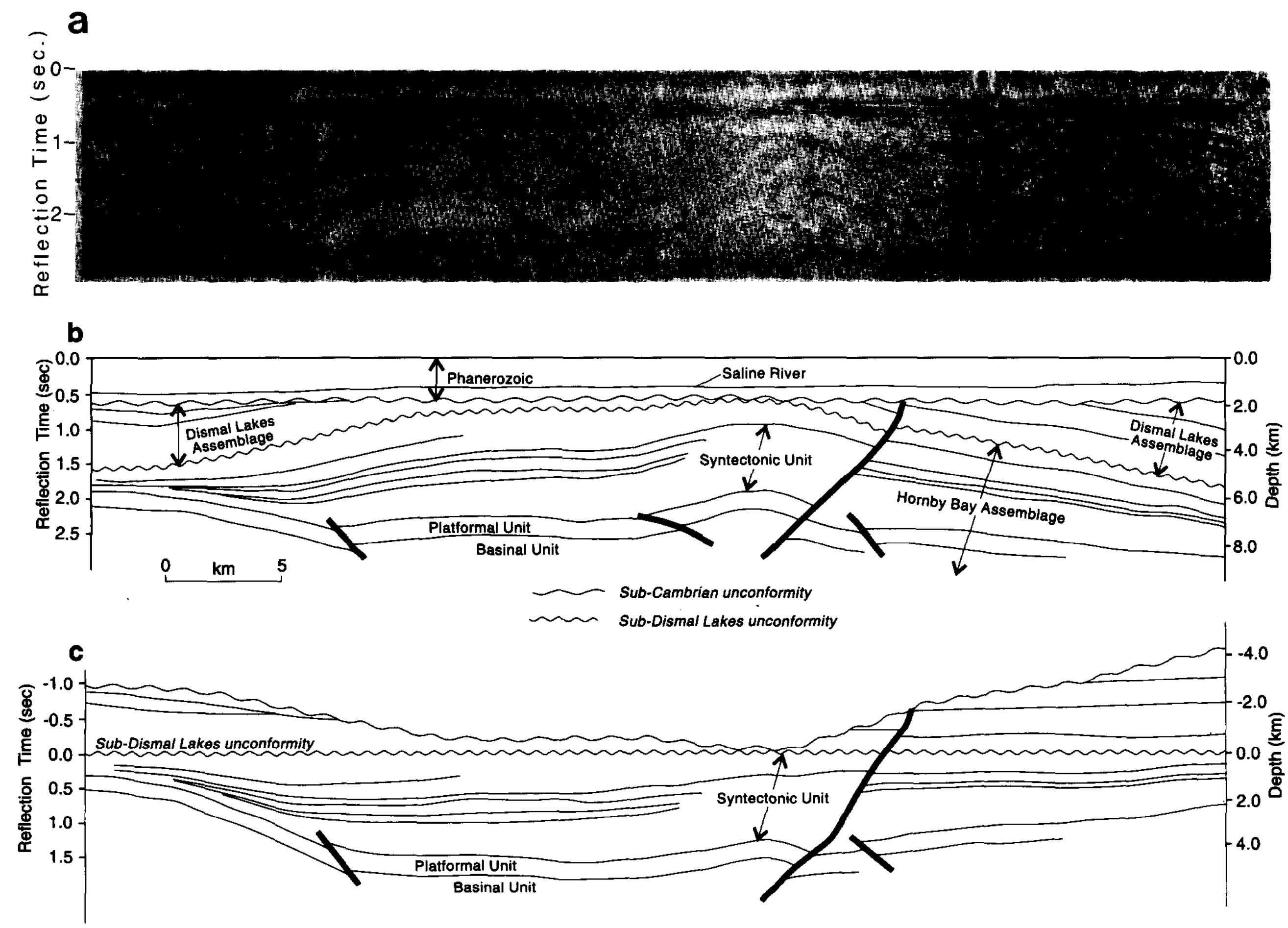

Fig. 10. Compression to compression positive inversion recorded on 1975 Dome Petroleum Line 9 (stacked). For location see Fig. 2. (a) Uninterpreted. (b) Annotated to illustrate a syndepositional trough (see (c)) inverted as a post-orogenic anticline. (c) Line drawing of Line 9 flattened with sub-Dismal Lakes unconformity as datum to illustrate antecedent synclinal trough. Unconformity-bounded depositional wedges in Syntectonic Unit record progressive syndepositional uplift of the flanks of the synclinal basin during the Forward Orogeny.

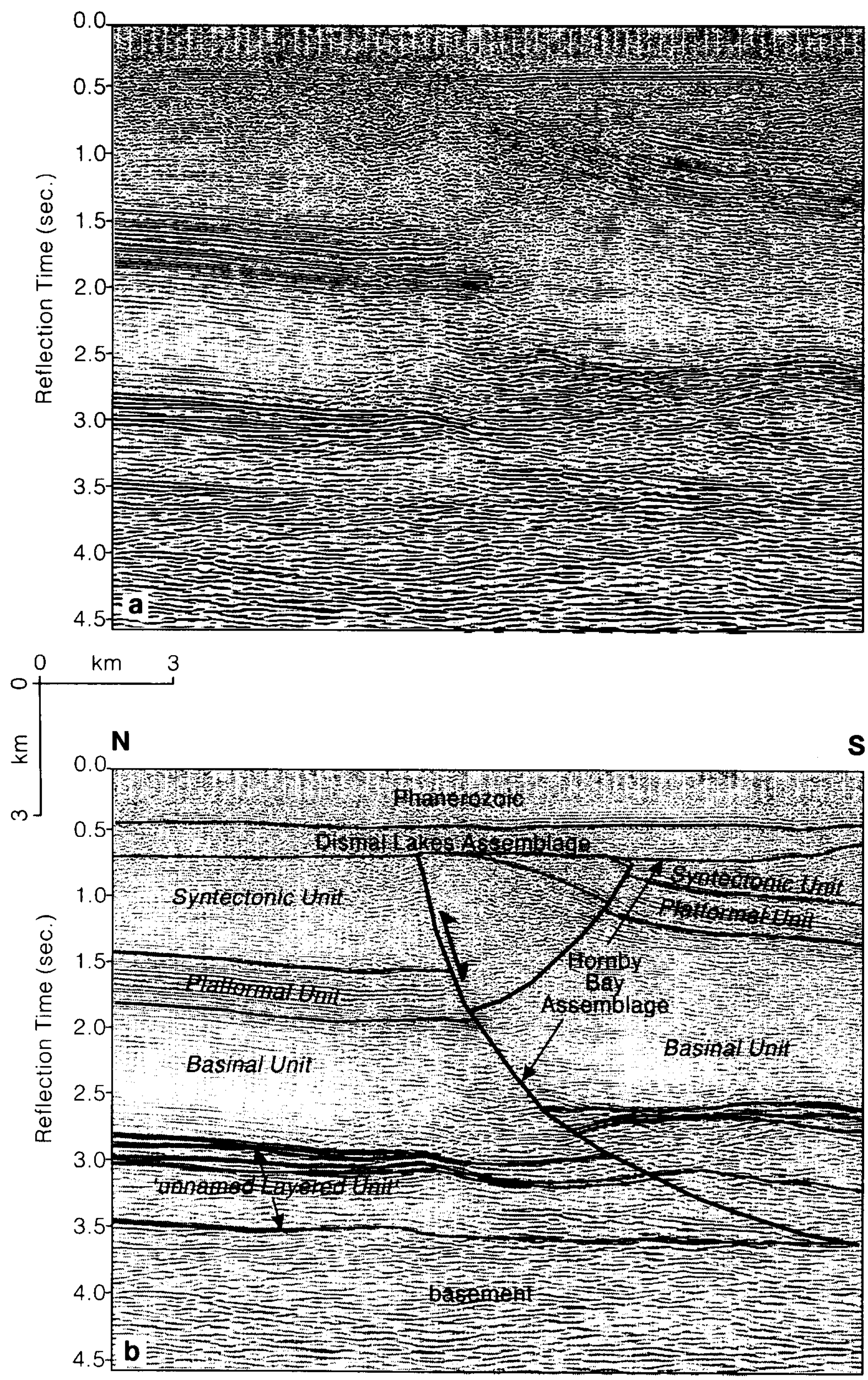

Fig. 6. Total positive inversion recorded on 1975 Hudson Bay Oil and Gas Line 7 (migrated). For location see Fig. 2. (a) Uninterpreted. (b) Annotated to illustrate a classical positive inversion structure. Abrupt thickening of Basinal Unit across the fault indicates an antecedent basin-bounding extensional fault (see (c)). The basin was inverted during the Forward Orogeny by thrust reactivation of the fault. Note the small antithetic fault and related 'pop-up' structure. Note double-headed displacement arrow; solid head indicates more-recent movement. (c) Flattened with top of Basinal Unit as datum to illustrate approximate original half-graben configuration. Flattening was accomplished by independently adjusting the hangingwall and footwall sections by vertical trace movement, followed by cut-and-paste horizontal restoration. Although the restored section could not be balanced with this procedure (note the gap between hangingwall and footwall), the reconstruction nonetheless illustrates the dramatic thickening of Basinal Unit in the half-graben.

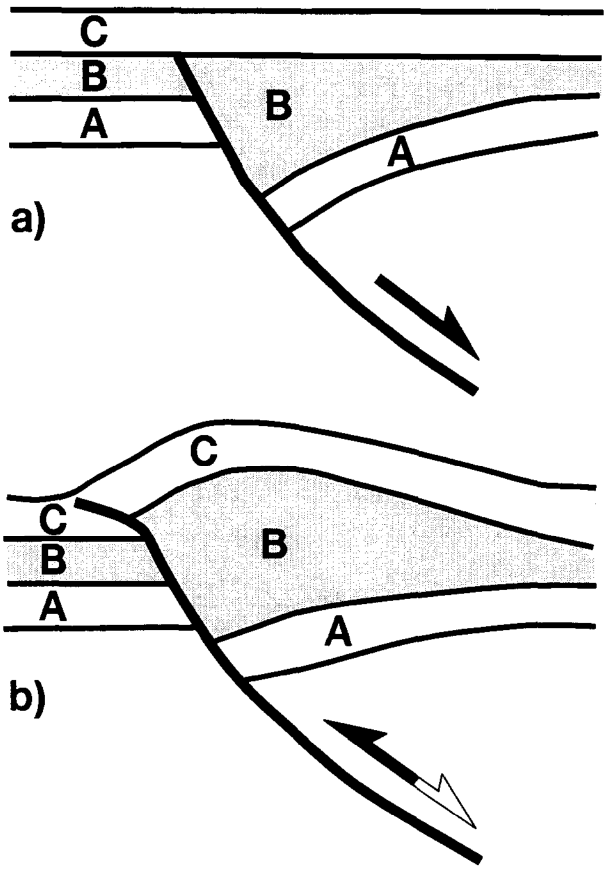

Fig. 3. Schematic diagram of classical (a) half-graben and (b) positive inversion structure. A, B and C are stratigraphic sequences: A, prerift; B, synrift; C, postrift sequence. Diagram after Williams *et al.* (1989).

three units are reliable markers across most of the area (see Figs. 5–8 and 10). We interpret the Basinal Unit to be the distal equivalent to the deltaic Lady Nye Formation found on the homocline, although it may also include counterparts of the older Big Bear and Fault River formations (Fig. 4). The unit was deposited, at least in part, during a period of extensional tectonics as marked by syndepositional half-grabens (see Figs. 5 and 6).

The middle unit of the Hornby Bay Assemblage, representing a stable depositional environment, hence the name Platformal Unit, is correlated with the platformal East River Formation comprising stromatolitic dolomites on Coppermine Homocline (Fig. 4). The subsurface Hornby Bay Assemblage was deformed during a major intracratonic compressional event, the Forward Orogeny, which occurred late in 'Hornby Bay time'. The orogeny produced basement-involved anticlines and thrust blocks, with structural relief as great as 6 km, and broad intervening synclinal basins. Structural style is similar, though of smaller scale, to that of the Rocky Mountain foreland of the U.S.A. (e.g. Lowell 1983, Rodgers 1987). The uppermost unit of the Hornby Bay Assemblage (Syntectonic Unit) was deposited in conjunction with deformation such that strata progressively onlapped growing Forward Orogeny structures (e.g. Figs. 7 and 10). Structures (e.g. Fig. 9) mapped on Coppermine Homocline (Ross & Kerans 1989) are also considered (Cook & MacLean 1995) to represent the Forward Orogeny, and the Syntectonic Unit is considered a counterpart to the syntectonic Kaertok Formation on the homocline. The Kaertok is dated at 1663 Ma (Bowring & Ross 1985), which tentatively dates the Syntectonic Unit, and the Forward Orogeny (Fig. 4). One of the earlier extensional half-grabens was inverted (classical half-graben inversion of Williams *et al.* 1989), during the Forward Orogeny (see Fig. 6).

A plate-boundary collisional zone related to the intracratonic Forward Orogeny may be represented by the Racklan Orogeny which deformed Wernecke Supergroup in the northern Canadian cordillera. New isotopic data from diabase dikes indicate that the Wernecke Supergroup is older than previously thought, probably Early Proterozoic (D. J. Thorkelson & J. K. Mortensen 1995, pers. comm.). If the dikes also post-date the Racklan deformation, the Racklan could be broadly related to the Forward Orogeny. The Forward Orogeny was followed by a period of epeirogeny, regional peneplanation and deposition of another major assemblage (Dismal Lakes Assemblage) which we correlate with the Dismal Lakes Group (Fig. 4). A phase of continental extension followed deposition of the Dismal Lakes during which large half-grabens developed, some of which inverted Forward Orogeny thrusts (negative inversion). Recognition of pre-unconformity compression and post-unconformity extension in the subsurface and on Coppermine Homocline is an important element in our correlation rationale.

Another period of erosion was followed by the deposition of a third assemblage including the Tweed Lake basalts, which are correlated (Sevigny *et al.* 1991) with the Copper Creek Formation comprising about 3 km of plateau basalts in the Coppermine River Group (Fig. 4). The Copper Creek and its 1267 Ma feeder dikes (the Mackenzie dike swarm) represent an extensional event that is weakly expressed by small post-basalt extension faults in the subsurface.

On Coppermine Homocline the Coppermine River Group is overlain unconformably by the Shaler Supergroup (Rainbird *et al.* 1994) which represents a fourth cycle of deposition. In the subsurface the Shaler may be represented by a couple of thin outliers in the western part of the area. It may also occur, but has not been identified, in the northern part of the study area adjacent to Brock Inlier. A post-Shaler compressional phase of long-wavelength folding (wavelengths of 30–90 km) affected subsurface strata, and inverted two earlier basins. One was an early half-graben (classic positive inversion); the other was a Forward Orogeny syntectonic synclinal basin inverted as an anticline (atypical positive inversion, compression–compression).

The long-wavelength folds were truncated during a fourth period of epeirogenesis and erosion which preceded Lower Cambrian marine incursion and deposition of basal Cambrian sands and younger Phanerozoic strata. Cretaceous–Tertiary 'Laramide' tectonism generated the faulted anticlines of Colville Hills, some 200 km landward of the Mackenzie Mountains front, by inferred transpressive reactivation of ancestral Proterozoic faults (MacLean & Cook 1992). Some of these anticlines represent mild inversion of Proterozoic half-

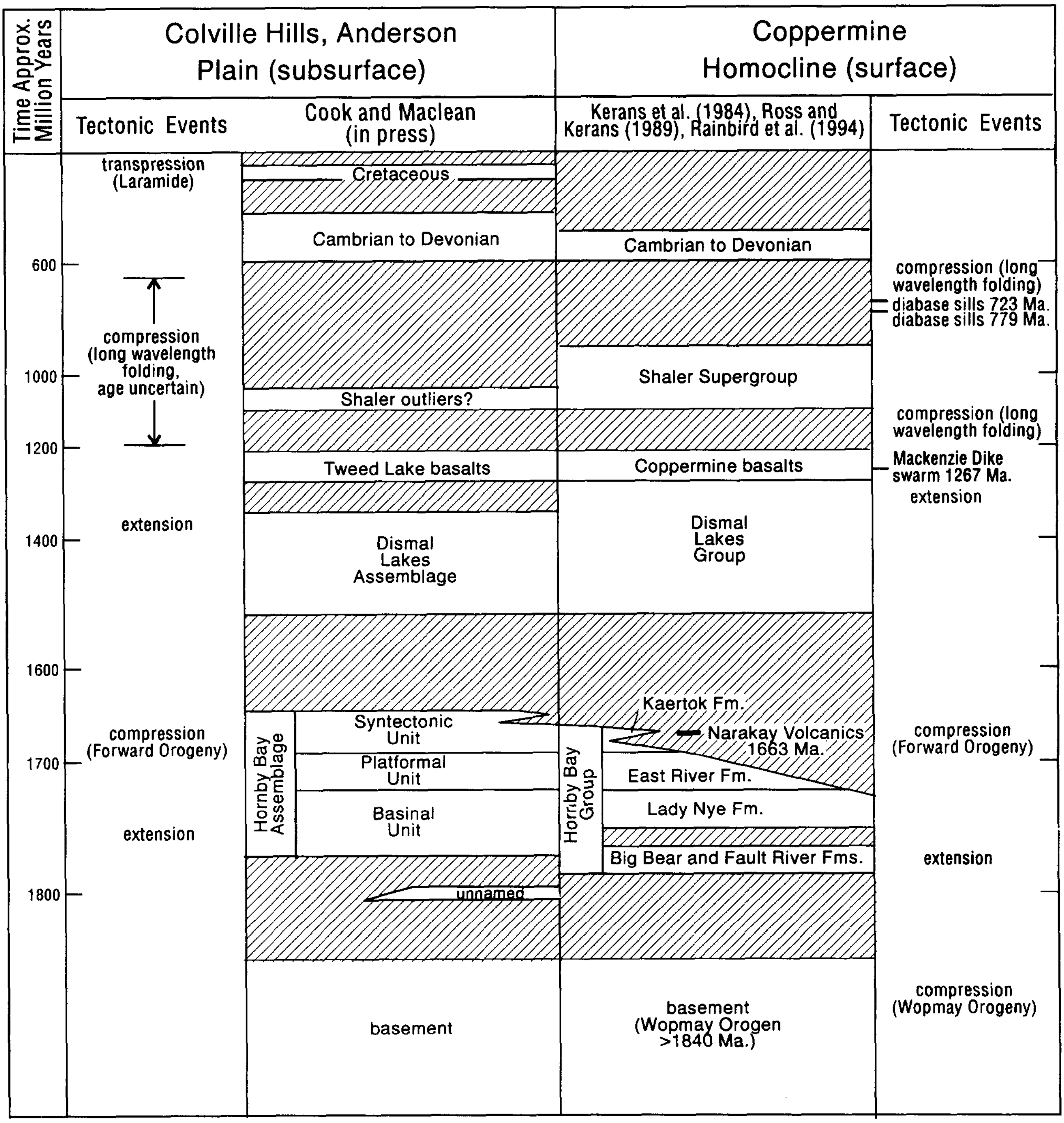

Fig. 4. Stratigraphic and tectonic correlation chart.

grabens which were themselves products of negative inversion of Forward Orogeny thrust faults (double inversion, negative/positive).

CLASSICAL POSITIVE HALF-GRABEN INVERSION

Crustal extension during deposition of the Basinal Unit of the Hornby Bay Assemblage was manifested regionally as a variably deep (3–6 km) sedimentary basin (Cook & MacLean 1995). Extension was mostly distributed across subsidence hinge zones with few faults recorded at the scale of observation, but in a few exceptions was expressed as half-graben growth faults of which at least two were inverted during subsequent compression.

In our best example of a half-graben (Fig. 5), the thickness of the Basinal Unit changes abruptly from about 3.9 km west of the fault, to about 4.5 km in the half-graben. Pre-rift (parallel to the base of the unit), synrift (depositional wedge), and post-rift (parallel to the top of the unit) sequences are all easily identified (compare Fig. 5b with Fig. 3) and show that extensional displacement occurred midway through deposition of the unit. Extension was completed well before deposition of the overlying uniform blanket of the Platformal Unit. This half-graben was slightly inverted during later compression which folded the Platformal Unit and younger strata into a gentle anticline with amplitude of about 900 m and wavelength of about 30 km. This would be considered a mild inversion by Williams *et al.* (1989).

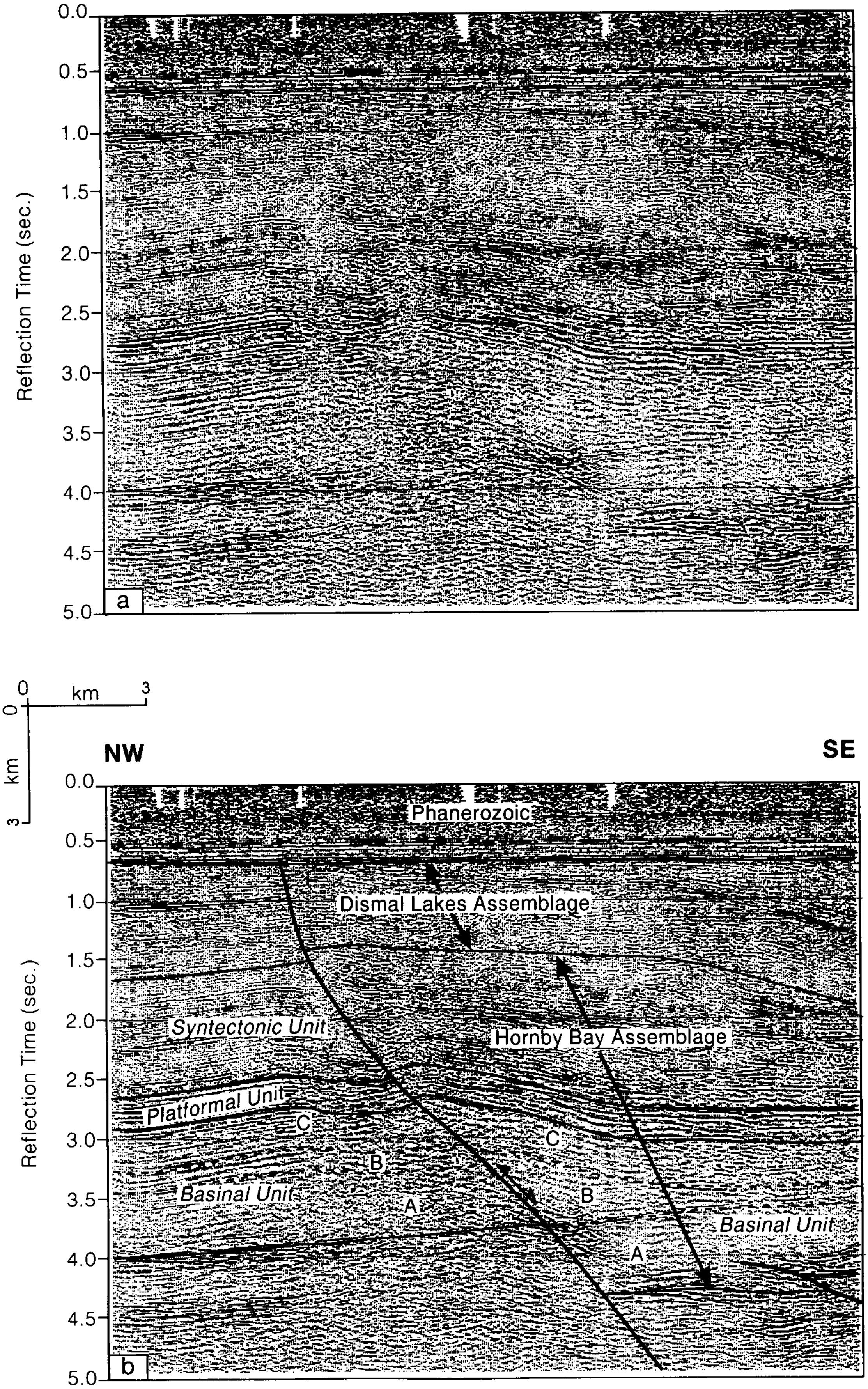

Fig. 5. Mild positive inversion recorded on 1984 Petro-Canada Line 81-X (migrated). For location see Fig. 2. (a) Uninterpreted. (b) Annotated to illustrate mildly inverted half-graben: A, prerift; B, synrift; C, postrift sequence (compare with Fig. 3). Note double-headed displacement arrow; solid head indicates more-recent movement.

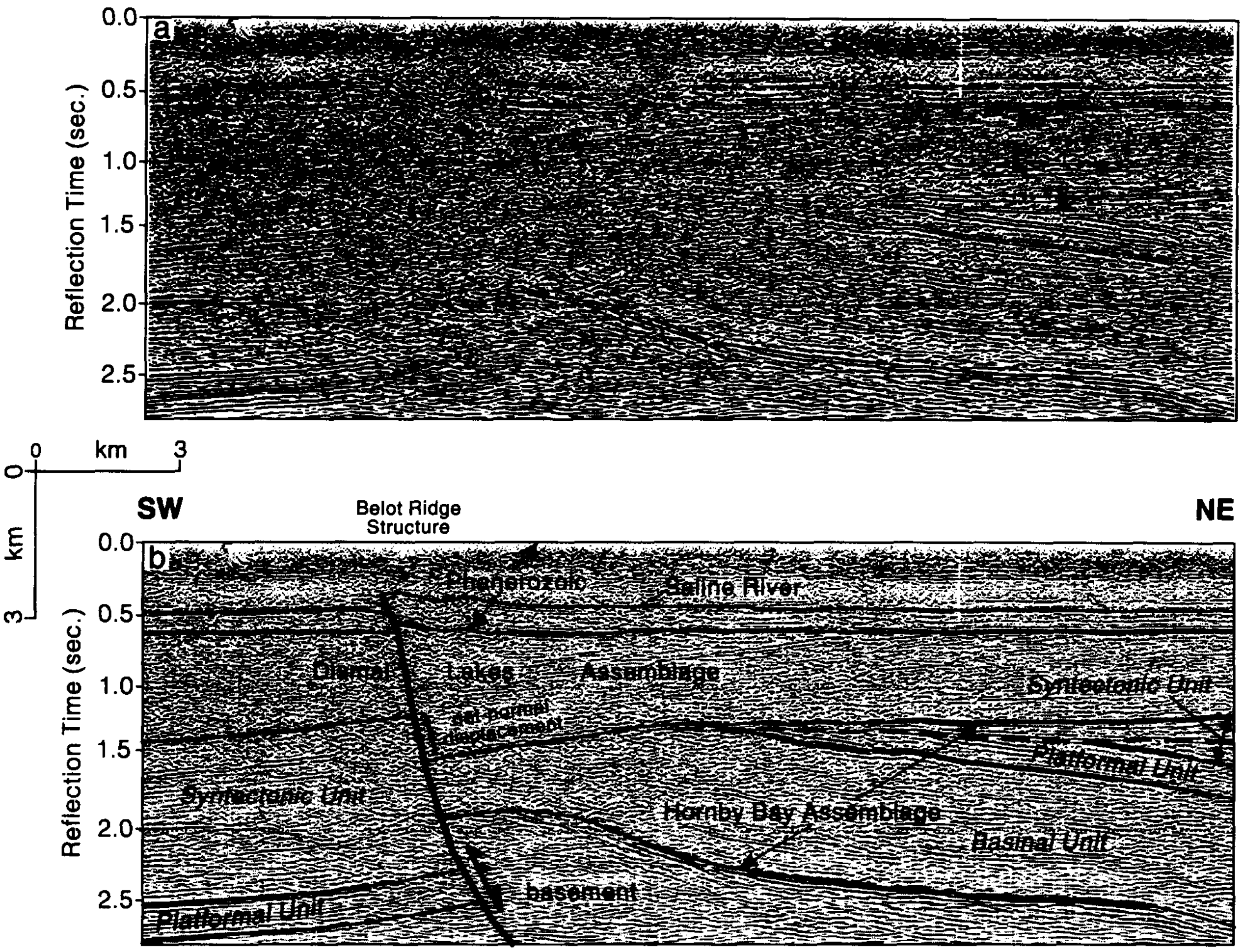

Fig. 7. Negative/positive double inversion recorded on 1983 Forward Resources Inc. Line FR-14 (migrated). For location see Fig. 2. (a) Uninterpreted. (b) Annotated to illustrate a double inversion structure. The Laramide faulted anticline (Belot Ridge structure) is a mild positive inversion of a half-graben which is itself a negative inversion of a Forward Orogeny thrust uplift. Note triple-headed displacement arrow; solid head indicates most-recent movement.

A more impressive example of classical inversion resembles a simple Forward Orogeny thrust fault in its present configuration (Fig. 6b), but abrupt thickening of the Basinal Unit across the fault indicates the presence of an ancestral half-graben. In this case inversion was total; in fact, contractional reactivation more than recovered the extensional offset of the Basinal Unit. The configuration of the half-graben is approximately restored (Fig. 6c) by flattening the section with the base of the Platformal Unit as datum. The flattening method does not provide a balanced section but nonetheless demonstrates the dramatic thickening of the Basinal Unit across the fault.

NEGATIVE INVERSION OF FORWARD OROGENY THRUST FAULTS

Basement-involved, thrust uplifts of the Forward Orogeny (Cook & MacLean 1995) were peneplaned and unconformably overlain by the Dismal Lakes Assemblage. Some suffered post-Dismal Lakes negative inversion with consequent development of half-grabens utilizing ancestral thrusts. Three examples, two subsurface and one surface, are illustrated. In an example of mild inversion (Fig. 7), extensional offset was much less than the earlier compressional displacement, and the ancestral Forward Orogeny uplift was retained as a high-angle thrust block. In an example of total inversion (Fig. 8b) extensional displacement was great enough to nullify the effect of compression and to mask the Forward Orogeny thrust block. The sub-Dismal Lakes unconformity shows extensional offset of about 3.6 km (1.2 sec.) whereas the Platformal Unit is offset only about 1.8 km (0.6 sec.). The difference is due to the presence of the ancestral west-side-up Forward Orogeny thrust fault, with structural relief of about 1.8 km, which is revealed by restoring the sub-Dismal Lakes unconformity to horizontal (Fig. 8c).

Another example of mild negative inversion is found on a geological map of Hornby Bay and Dismal Lakes groups on Coppermine Homocline (Ross & Kerans 1989). There, an east-side-up compressional uplift juxtaposes crystalline basement with overturned Hornby Bay Group strata (Fig. 9). The structure was truncated by erosion such that Dismal Lakes Group unconformably overlies crystalline basement in the eastern uplifted block, and overturned Hornby Bay Group in the western footwall. However, the unconformity has itself been

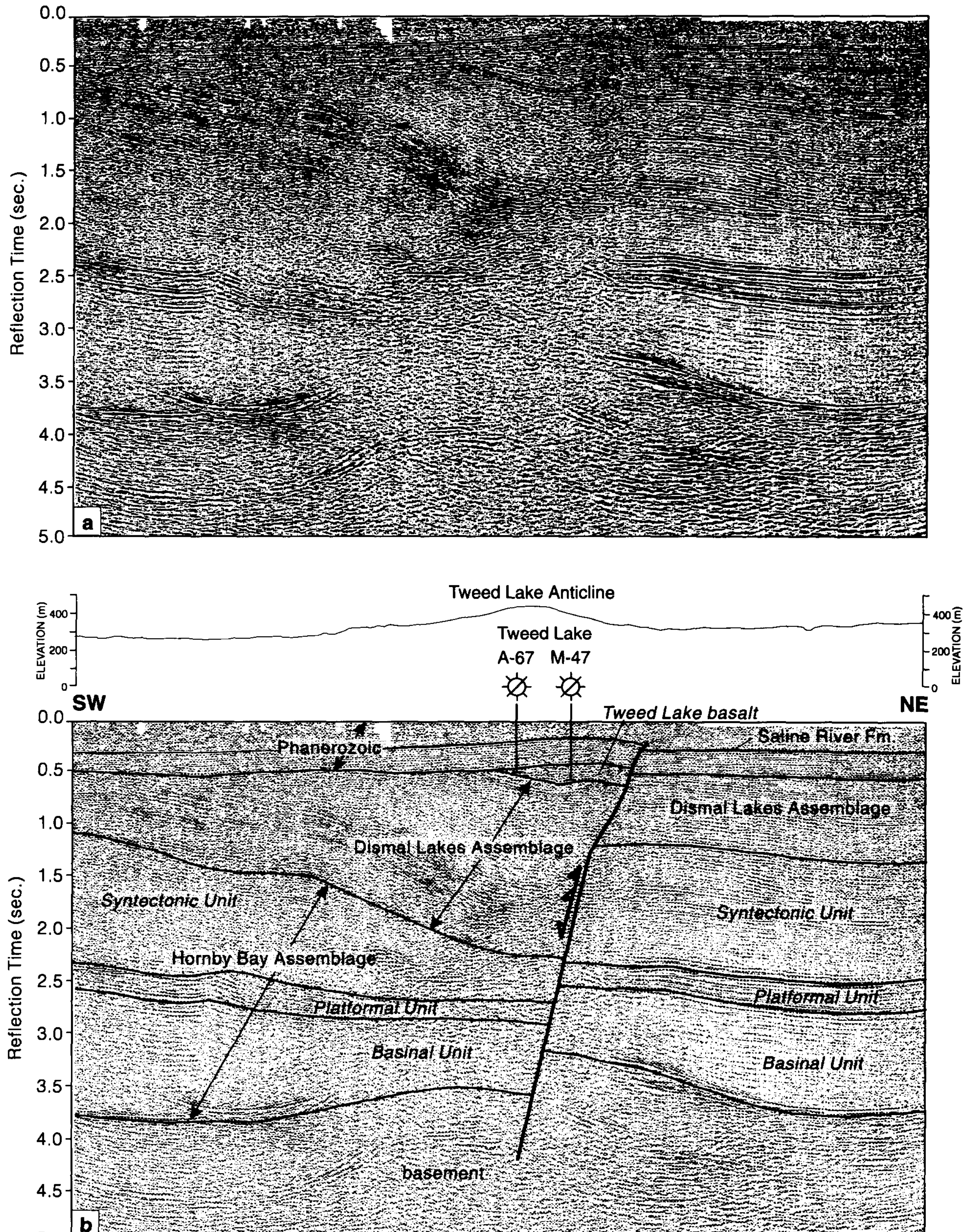

Fig. 8. Negative/positive double inversion recorded on 1979 Petro-Canada Line 116A/110A (migrated). For location see Fig. 2. (a) Uninterpreted. (b) Annotated to illustrate a double-inversion structure. The Laramide Tweed Lake anticline is a mild positive inversion of a large half-graben which is, itself, a total negative inversion of a Forward Orogeny thrust fault (see (c)). Note triple-headed displacement arrow; solid head indicates most-recent movement. (c) Flattened with sub-Dismal Lakes unconformity as datum. Removal of the extensional phase reveals a Forward Orogeny thrust block with uplift of about 2.1 km (0.7 sec.). Flattening by vertical trace movement restores only the vertical component of deformation; the curved fault is schematic.

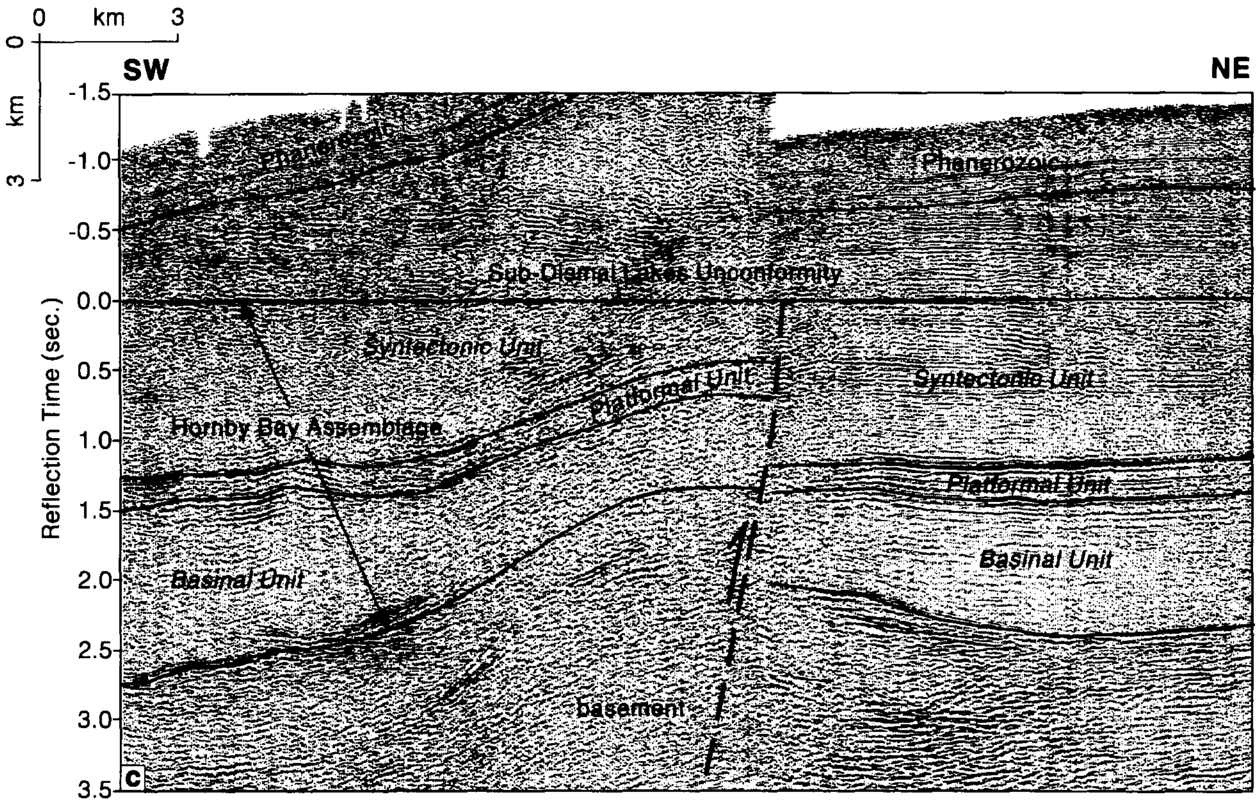

Fig. 8. *Continued.*

offset by post-orogenic east-side-down mild inversion. The identical structural histories of this and certain subsurface structures (e.g. Figs. 7b and 8b) are an important part of the rationale for correlating from the subsurface to outcropping strata (Cook & MacLean 1995).

DOUBLE INVERSION, POSITIVE FOLLOWING NEGATIVE

Laramide positive inversions are presented here out of geologic sequence because they are structurally linked to their negative inversion antecedents. Late Cretaceous/Tertiary 'Laramide' faulted anticlinal ridges of the Colville Hills (Fig. 2) were the principal exploration targets responsible for the acquisition of the seismic records on which this paper is based. Gas has been discovered in three structures (Fig. 2). MacLean and Cook (1992) considered the anticlines to be transpressional, having been generated by right-lateral strike-slip reactivation of ancestral Proterozoic faults. Most Laramide structures simply reactivate earlier Forward Orogeny thrusts, but some, including the gas-bearing Tweed Lake anticline, comprise mild inversion of half-grabens (Figs. 7b and 8b) that were themselves products of

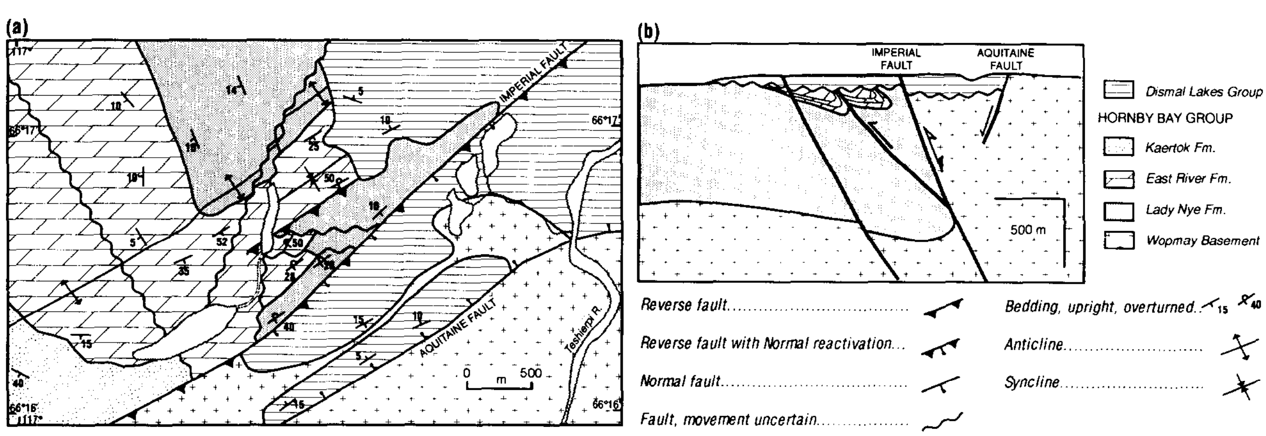

Fig. 9. Mild negative inversion of a 'Forward Orogeny' structure mapped on Coppermine Homocline. (a) Map after Ross & Kerans (1989, Inset A). For location see Fig. 1. (b) Schematic cross-section across (a). Crystalline basement is faulted against overturned Hornby Bay Group strata, and both are unconformably overlain by gently dipping Dismal Lakes Group. Post-Dismal Lakes normal movement mildly inverts the structure. Note double-headed displacement arrow; solid head indicates more-recent movement.

negative inversion. Those Laramide structures with underlying two-phase ancestral faults are thus the products of double inversion.

COMPRESSIONAL INVERSION OF A COMPRESSIONAL SYNCLINE

The Forward Orogeny generated isolated anticlinal and thrust uplifts with broad intervening syntectonic troughs. The troughs were not noticeably affected by the post-Dismal Lakes extension noted above, but at least one was inverted into a broad anticline during renewed compression related to post-Coppermine Assemblage or post-Shaler Supergroup long-wavelength folding. In that example (Fig. 10) a synclinal basin about 30 km across and 4.8 km deep was filled during the Forward Orogeny, truncated by the sub-Dismal Lakes unconformity, and subsequently inverted, such that the unconformity now describes a broad arch with structural relief of about 4 km (1.3 sec.). The pre-inversion basin with flanking unconformities and onlapping syntectonic depositional wedges is more clearly illustrated by restoring the unconformity to horizontal (Fig. 10c). A small mid-basin faulted anticline apparently originated during the Forward Orogeny because it predated erosional truncation at the sub-Dismal Lakes unconformity (Fig. 10c). From regional considerations it is known that the stress field polarity changed from compressional to extensional to compressional, but the extensional phase had no detectable effect, at the scale of observation, on this structure. This inversion is thus atypical in that it was implemented by a renewal of compression rather than a reversal in stress field polarity.

CONCLUSIONS

Seismic data from the Colville Hills and adjacent plains, Northwest Territories, Canada, record a number of tectonic phases involving at least three reversals in stress field polarity during a prolonged (*ca* 1.7 Ga) history. Recognition of four types of tectonic inversions is the key to understanding the structural and tectonic history. In one type, early basin-extending half-grabens were inverted during subsequent compression (positive inversion). In another, Forward Orogeny thrust faults were reversed as normal faults to form extensional half-grabens (negative inversion). Some of those half-grabens were themselves mildly inverted during Laramide transpression (double inversion). One 'unconventional' inversion was not due to a reversal of tectonic polarity. There, a compressional synclinal trough was inverted as an anticline (compression–compression, positive inversion).

Restriction of the term 'inversion tectonics' to the inversion of half-grabens seems too confining. In this paper we have applied descriptive rather than generic definitions. Thus, 'positive inversion' applies to any basin, or zone of subsidence and sedimentation, that was converted to a zone of uplift and net erosion whether or not that reversal was implemented by a reversal of tectonic polarity. Correspondingly, 'negative inversion' applies to any area of uplift that was converted to a sediment-receiving basin.

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