Geometry and kinematics of inversion tectonics

G. D. Williams, C. M. Powell & M. A. Cooper

SUMMARY: Positive inversion tectonics involves the reversal of extensional fault movement during contractional tectonics. Basin stratigraphy developed before, during and after extensional fault movements may be described as pre-, syn- and postrift sequences. Growth fault activity may be graphically displayed using thickness changes in stratigraphic intervals from fault footwall to hanging wall. Alternatively, it may be recorded using a hanging wall displacement/distance plot. Contractional reactivation of extensional faults puts progressively older synrift markers into net contraction. The point of change from net extension to net contraction is the null point. Its position in the synrift stratigraphy may be used to quantify the inversion ratio, which is defined as the ratio of contractional to extensional movement. Negative inversion is the reactivation in extension of a significant portion of an existing contractional system. Stratigraphic separation diagrams constructed from geological maps may be used to define the null point of individual faults and to quantify their inversion ratio.

Basic nomenclature

Structural inversion occurs when basin-controlling extensional faults reverse their movement during compressional tectonics, and, to varying degrees, basins are turned inside out to become positive features. The result is that individual faults may retain net extension at depth and show net contraction associated with anticline growth in their upper portions (Fig. 1). The converse is also possible. Thus inversion can be considered in terms of both positive (uplift) and negative (subsidence) senses relative to the immediately preceeding history of a fault system (Glennie & Boegner 1981).

In this paper, a fault is considered to be of extensional mode if it involves the displacement of an approximately horizontal marker horizon in the fault hanging wall below its pre-deformational regional elevation, and is of contractional mode if a hanging wall marker is displaced above its regional elevation (Fig. 2). A marker horizon may consist of an originally horizontal or subhorizontal stratigraphic interface, a marker bed on a geological cross-section, or a sequence boundary on a seismic reflection section. This definition is simple; it does not involve discussions of net slip of the fault and closely resembles fault dip separation.

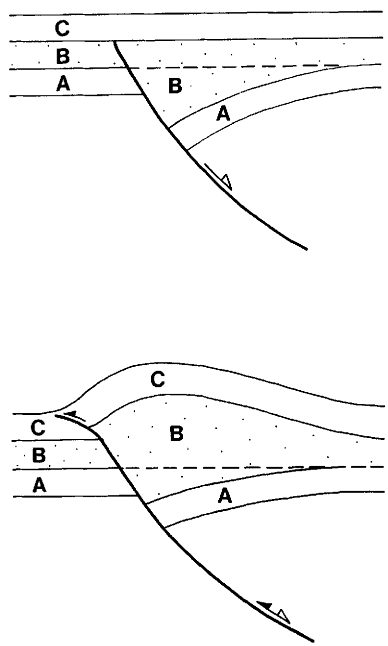


FIG. 1. Schematic diagram of a classical positive inversion structure. A, B and C are stratigraphic sequences. A, prerift; B, synrift; C, postrift sequence.

In our definition we consider apparent dip as portrayed in a cross-section or seismic section, rather than true fault dips. Cross-sections through a fault in any direction will reveal its extensional or contractional mode if our definition is applied. Only a perfectly bed-parallel fault (a flat on flat) and a perfectly strike-slip fault is neither extensional nor contractional and may be considered a neutral mode fault. A fault which appears vertical in the plane of a section cannot be classified in this scheme. Because net slip is not considered in this definition we may apply the contractional/extensional nomenclature to all faults including those

From COOPER, M. A. & WILLIAMS, G. D. (eds), *Inversion Tectonics*, Geological Society Special Publication No. 44, 3–15

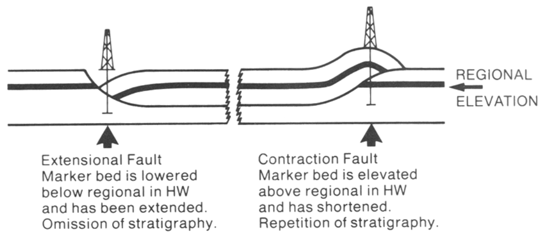


FIG. 2. Definition of A, extensional and B, contractional faults.

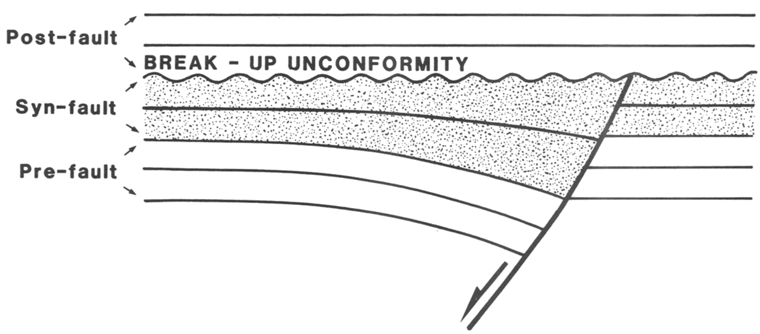


FIG. 3. Schematic diagram of stratigraphy accumulated before, during and after extensional fault movement. The break-up unconformity is shown as a wavy line at the top of the synrift sequence.

generated in a strike slip system at transpressive and transtensional fault bends.

Structural inversion involves fault movements giving rise to a switching of fault mode. A perfect reversal of fault net slip is unlikely and most inversion structures probably result from superimposed oblique slip movements. Our definition may be used to separate individual fault modes and to analyse structural inversion and is preferable to existing, complex, fault nomenclature.

In this paper we shall consider both positive inversion of a stratigraphy accumulated in extensional regimes and the negative inversion of thrust systems.

Extensional faulting

Stratigraphy built up on continental margins or in continental extensional basins, in its simplest form, may exhibit three distinct sequences (Fig. 3).

1 A prerift sequence is deposited prior to any extensional fault movement.

2 A synrift sequence is deposited during extensional faulting. Marked stratigraphic thickness changes from fault footwall to hanging wall are indicative of growth faulting.

3 A postrift sequence is deposited after the cessation of extensional faulting. The postrift sequence may be deposited after a period of non-deposition and/or erosion marked by a break-up unconformity which may remove part of the synrift sequence.

Percentage interval change

A listric extensional fault active during sediment deposition gives rise to a rollover anticline in the hanging wall above the curved portion of the fault (Hamblin 1965; Gibbs 1984). A rotational fault block model dominated by planar faults gives a similar effect. A wedge of synrift sediments thickens towards the fault in either case (Fig. 3). The fault movement history is recorded in stratigraphic thickness changes between footwall and hanging wall. This may be graphically displayed by plotting changes in stratigraphic thickness (footwall to hanging wall) against chronostratigraphy (Fig. 4A) (Beach 1984). Percentage interval change (I) is given by:

$$I = \frac{I_h - I_f}{I_f} \times 100 \quad (1)$$

where I_f is the thickness of a stratigraphic interval in the footwall of an extension fault and I_h is the thickness of the same interval in the hanging wall. Both I_h and I_f are measured perpendicular to bedding in the plane of the section. They should be measured immediately adjacent to the fault.

Peaks in the resulting curve correspond to periods of maximum fault activity in the synrift sequence. A break-up unconformity will remove part of the synrift sequence. In this case, the fault activity curve will be incomplete and will not return to the ordinate (Fig. 4B). The unconformity will remove a thickness of section which represents a greater time interval in the footwall than in the hanging wall. This is because the footwall represents a condensed stratigraphic sequence.

Displacement/distance

A synrift sedimentary sequence accumulated during growth faulting will show increasing extensional displacements of stratigraphic markers with depth. This may be graphically represented using a modification of the displacement/distance plot of Williams & Chapman (1983). Using the top of the synrift sequence as a reference point, distance along a fault to individual hanging wall markers can be measured. This effectively records hanging wall stratigraphic thicknesses. Hanging wall distance is plotted against displacement (or more correctly, dip separation) of individual markers. Both parameters are measured in the plane of the section and therefore represent *apparent hanging wall distance* and *apparent extensional displacement* (Fig. 5). A curve with a negative gradient results. Changes in gradient relate to variations through time of fault activity. In this respect, the curve is similar to the percentage interval change plot (Figs 4A & B). Because the prerift and postrift sequences were not accumulated during growth faulting, any fault dislocation of these sequences should show no dislocation changes. This yields a curve with an infinite gradient or a slope of 90° on the displacement/distance plot.

In the preceding discussion we have not considered effects such as sediment compaction or displacement gradients along individual faults. These important effects are quantifiable.

Positive inversion of extensional fault systems

Our definition of extensional, contractional and neutral mode faults relies upon the geometry of faults and of marker horizons relative to regional elevation in the plane of a cross-section or seismic reflection section. The contractional reactivation of an extensional mode fault leads to an apparent reversal of movement when considered in the plane of the section. Using a typical pre-, syn- and postrift stratigraphy accumulated before, during and after extensional fault movements, we now consider the geometry of the system during contraction. In this analysis we assume that the stratigraphy is complete and that no break-up unconformity is present.

Contractional fault movement immediately displaces the postrift sequence in the fault hanging wall above its pre-deformational regional elevation. Continued contractional movement on the fault progressively puts synrift marker horizons into contraction (Fig. 6A, B & C). This process occurs sequentially. Markers at the top of the synrift sequence regain their regional elevations and move into contraction before lower synrift markers. If contractional faulting is arrested during this process, the upper part of the synrift sequence may be in net contraction whilst the lower part remains in net extension. The net extensional and net contractional portions are separated by a synrift marker that has regained its regional elevation by contractional movement. This marker now appears unfaulted and this point on the fault is defined as the *null point*. Progressive contractional inversion of an extensional synrift sequence causes the null point to move down the synrift sequence.

Inversion ratio

It is possible to quantify the relative magnitudes of contractional and extensional movement measured in the plane of the section using the position of the null point in a synrift sequence. The inversion ratio (R_i) is defined as the ratio of contractional to extensional displacement. It may be calculated by considering the thickness of the hanging wall synrift sequence measured parallel to the fault and the position of the null point in this sequence (Fig. 7).

$$R_i = \frac{d_c}{d_h} \quad (2)$$

where d_h is the thickness of synrift sequence

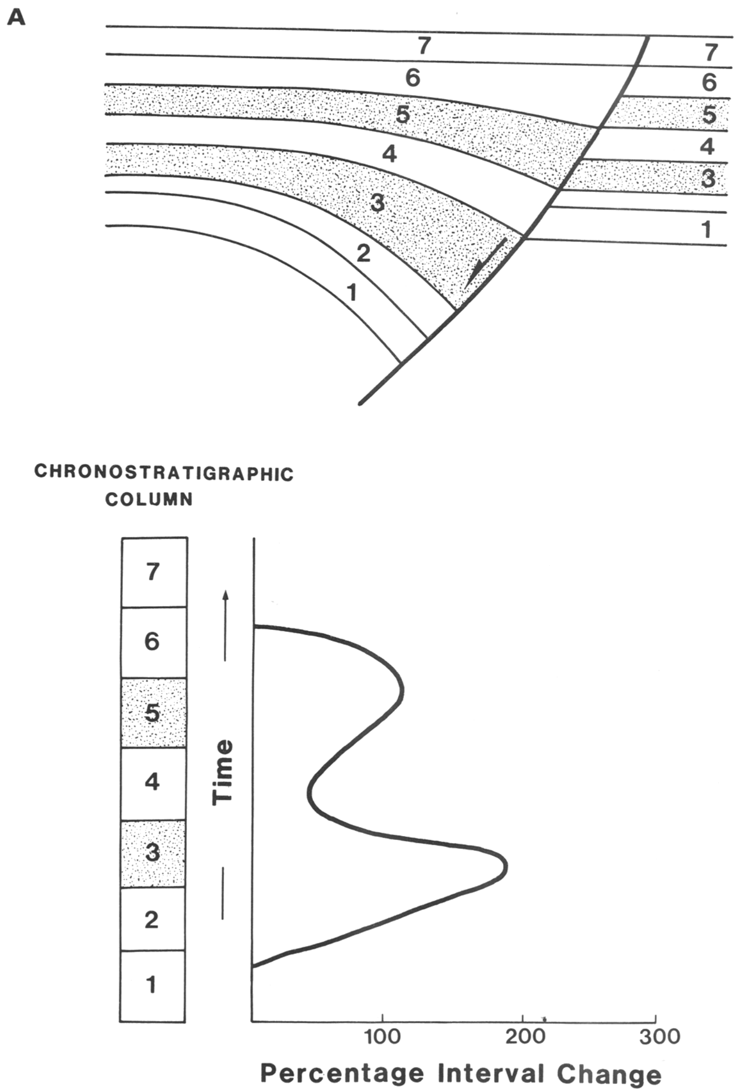


FIG. 4. 'Percentage interval change' plots; A, with no break-up unconformity; B, with break-up unconformity.

parallel to the fault and d_c is the thickness of synrift sequence in contraction (above the null point). We may rewrite this as:

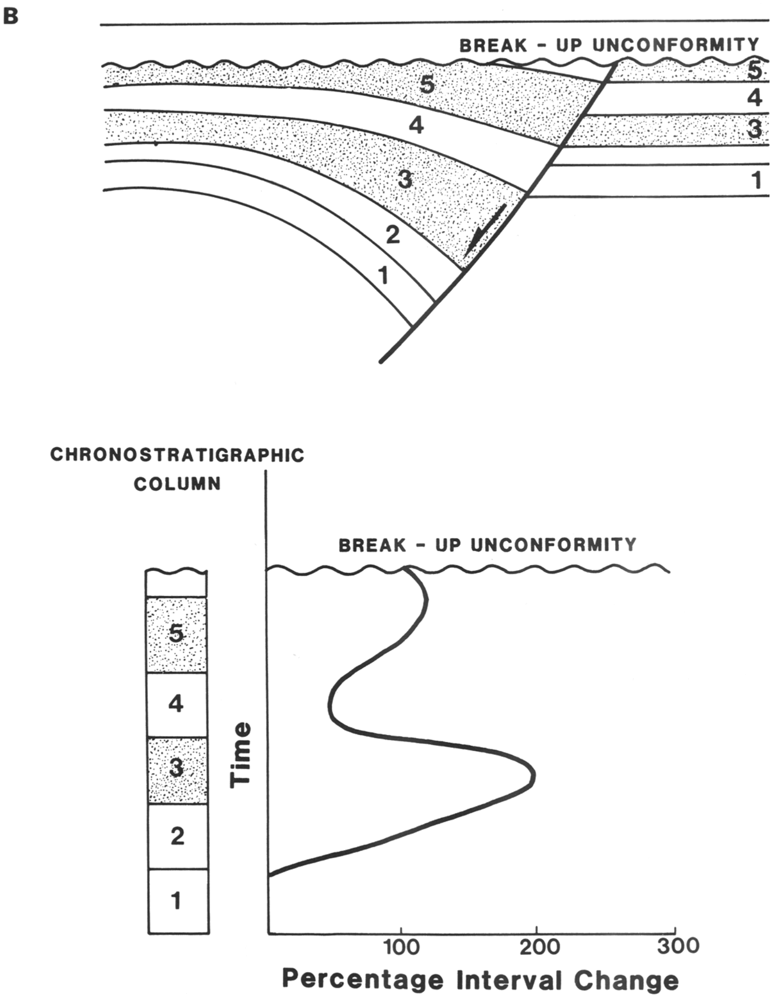
$$R_i = 1 - \frac{d_e}{d_h} \tag{3}$$

where d_e is the thickness of synrift sequence parallel to the fault below the null point.

From equations (2) and (3), it is seen that if the null point lies at the top of the synrift sequence, $R_i = 0$ ($d_c = 0$ and $d_e = d_h$). That is, no contractional inversion has occurred. If the null point is at the base of the synrift sequence, $R_i = 1$ ($d_c = d_h$ and $d_e = 0$). Total inversion of the synrift sequence has occurred and all markers in the prerift sequence have regained their pre-deformational regional elevations.

Displacement/distance

The displacement/distance plot (Fig. 5) may be further modified to graphically display inversion structures. Using the top of the synrift sequence as a reference datum, distance to



marker horizons is measured parallel to the fault in its hanging wall. Contractional displacement of markers is plotted to the left and extensional displacement is plotted to the right of the ordinate (Fig. 8). A curve with a negative gradient results, and the intercept of the curve with the ordinate defines the null point. The shape of this curve is a result of extensional tectonics, and gradient changes record variations in extensional fault growth. During progressive contractional inversion, the whole curve retains its form, but moves to the left. This causes the null point to move down the ordinate and effectively down section. The parameters d_h, d_c and d_e used in equations (2) and (3) may be read directly from this diagram (Fig. 8). An example of an inverted fault from the Gippsland Basin of SE Australia (Fig. 9) shows inversion of only one fault in an array of extensional faults (Davis 1983). The apparent inversion ratio of this structure is $R_i = 0.7$. However, because this figure is a time section the appropriate velocity function must be applied to convert the inversion ratio to its true value.

Negative inversion of contractional fault systems

The extensional reactivation of originally contractional systems appears to be less common than positive inversion. However, the reactivation may be only partial, and only evident in certain portions of the system. This can produce

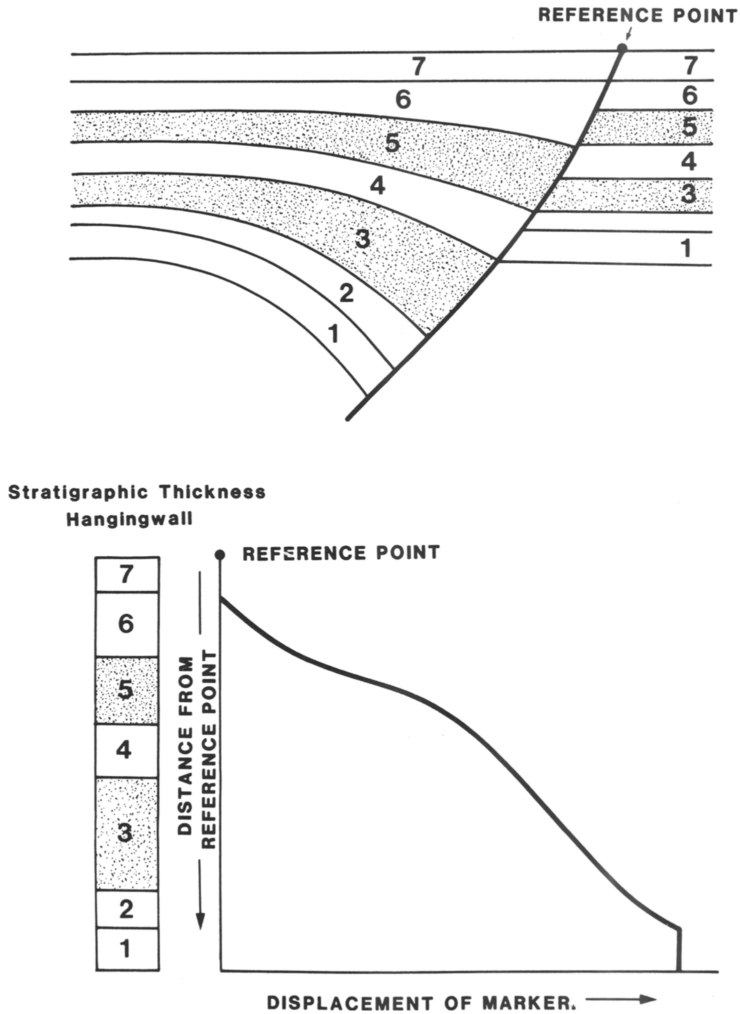


FIG. 5. Displacement/distance plot for the hanging wall of an extensional growth fault.

complex relationships between the portions of faults that are in net extension and those in net contraction. This can be conveniently analysed using the concept of null points and null zones (or neutral faults). These are fault segments which show neither contraction nor extension.

No re-use of the thrust system (Fig. 10)

In this case, an extension fault cuts through a thrust system and may detach at a deeper level. If the extension fault cuts through the thrust system without intersecting repeated stratigraphy across a thrust (which is possible though unlikely) then no null point exists. If the extension fault cross cuts thrust-repeated stratigraphy, then in the early stages of extension the footwall cutoff of the thrust which produces repetition will be the null point. The newly formed extension fault will show contraction below this point. A lower null point which marks the return to extension will be located at the footwall cutoff of the stratigraphically lowest thrusted bed. Both null points will disappear when the hanging wall cutoff of the stratigraphically highest thrusted bed coincides with the upper null point. At this point the extensional fault will be entirely in net extension with no local apparent contraction.

Partial re-use of single thrust (Fig. 11)

In this case an extensional fault has developed with a branch point to the thrust system at the

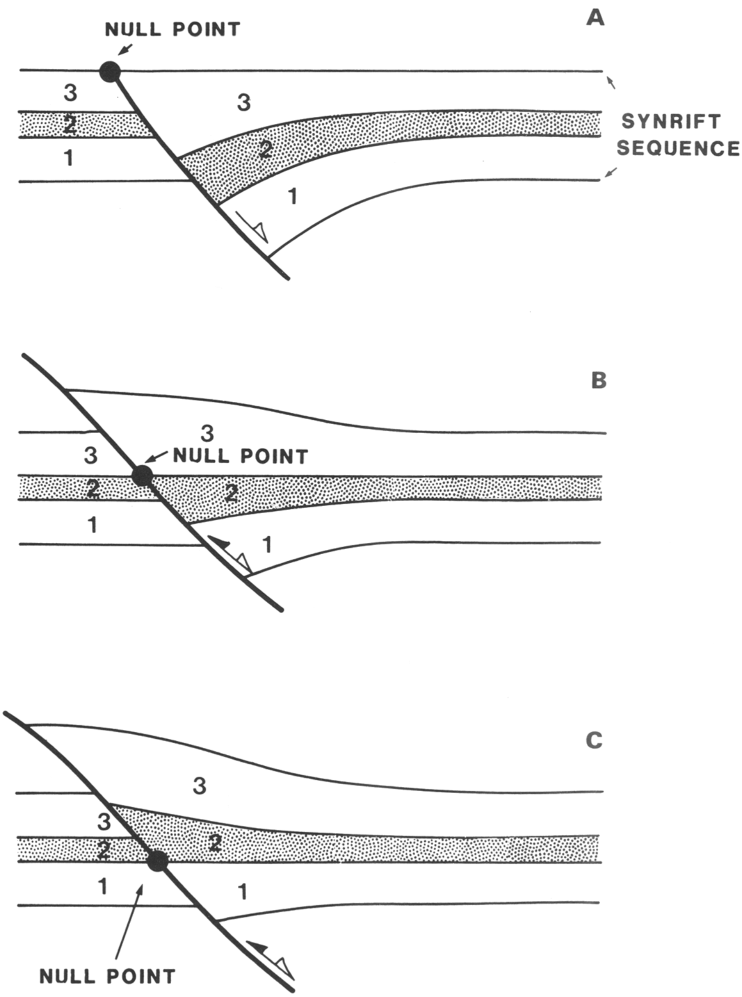


FIG. 6. Sequential diagrams to show the contractional inversion of an extensional fault. The null point moves progressively down the synrift sequence with increased contractional inversion.

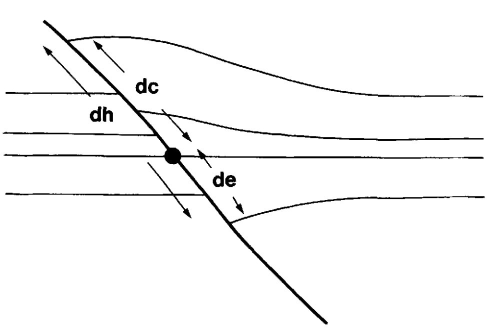


FIG. 7. Parameters used in equations (2) and (3) for the calculation of inversion ratio.

top of the thrust ramp. The null point of the system is this branch point. However, with continued extensional movement, the null point will disappear once the hanging wall cutoff of the stratigraphically highest repeated bed coincides with the branch point. At this position, the null point becomes a null zone which extends down the fault. Any additional extension causes this zone to disappear and the whole thrust ramp becomes extensional.

This does not mean that all the contractional slip has been reversed because the null point is derived from stratigraphic relationships. The extensional fault has shortcut the thrust hanging wall leaving behind a thrusted portion in its

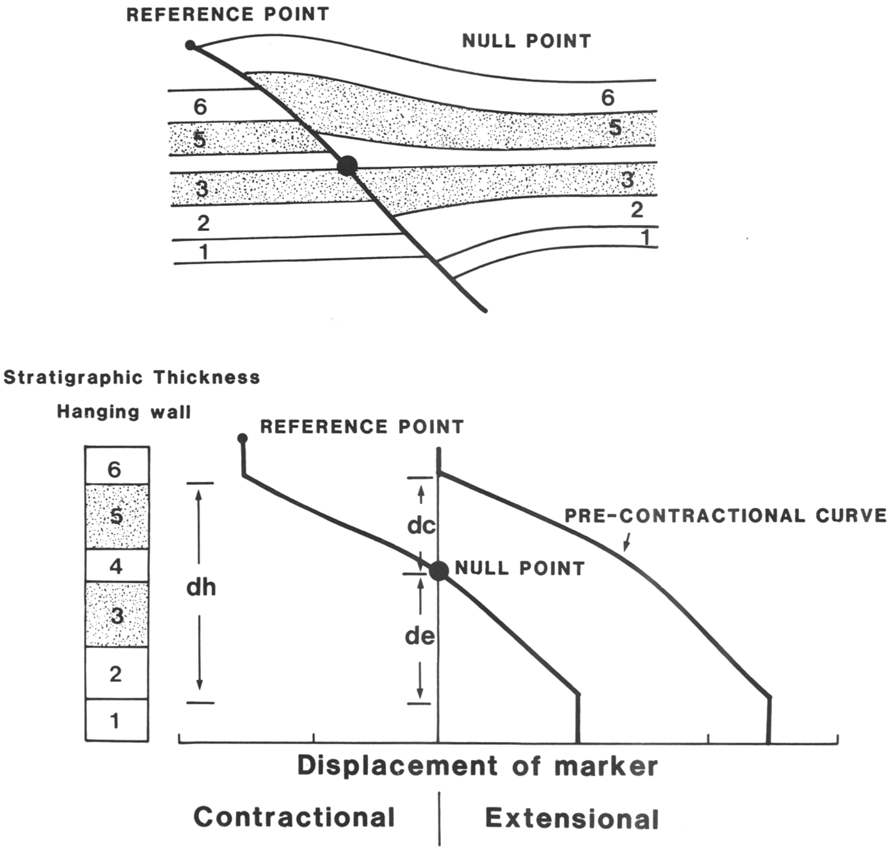


Fig. 8. Displacement/distance plot for a contractionally inverted extensional fault. Curve on right represents the situation prior to inversion. Parameters for equations (2) and (3) are shown.

footwall. If the erosion level was below that of the upper thrust plane then it would be impossible to detect the early thrust phase. The thrust/extension fault plane is a neutral fault showing neither contraction nor extension.

Partial reactivation of a complex thrust system (Fig. 12)

This thrust system comprises a major thrust (thrust 2) with a hanging wall imbricate (thrust 3). Thrust 1 has developed in the footwall of thrust 2 with a branch point at the base of a footwall ramp on thrust 2. Fig. 12 shows two stages in the progressive negative inversion of the thrust system. Thrust 1 is in net extension where it is a ramp, but turns into a neutral fault (a null zone) where it is parallel to bedding. When extensional reactivation has removed all the initial contraction of thrust 1, so that the hanging wall and footwall cutoffs re-match, then a null zone will exist for the whole length of thrust 1. Thrust 2 shows no extensional reactivation and thus has no null point. It remains in net contraction.

After the first increment of extension thrust 3 is still in net contraction until the null point is reached at the base of the extensional synrift package. With greater extension the null point migrates down the ramp until the hanging wall and footwall cutoffs of the repeated section rematch. At this point a null zone is created from the base of the synrift sequence to the next hanging wall ramp cutoff (Fig. 12B). This null zone will remain fixed until the cutoffs of the deeper thrust ramp are re-matched. At this stage, the contractional displacement on thrust 2, which was shortcut by extensional reactivation, has been completely removed by extension. With any additional extension, the whole

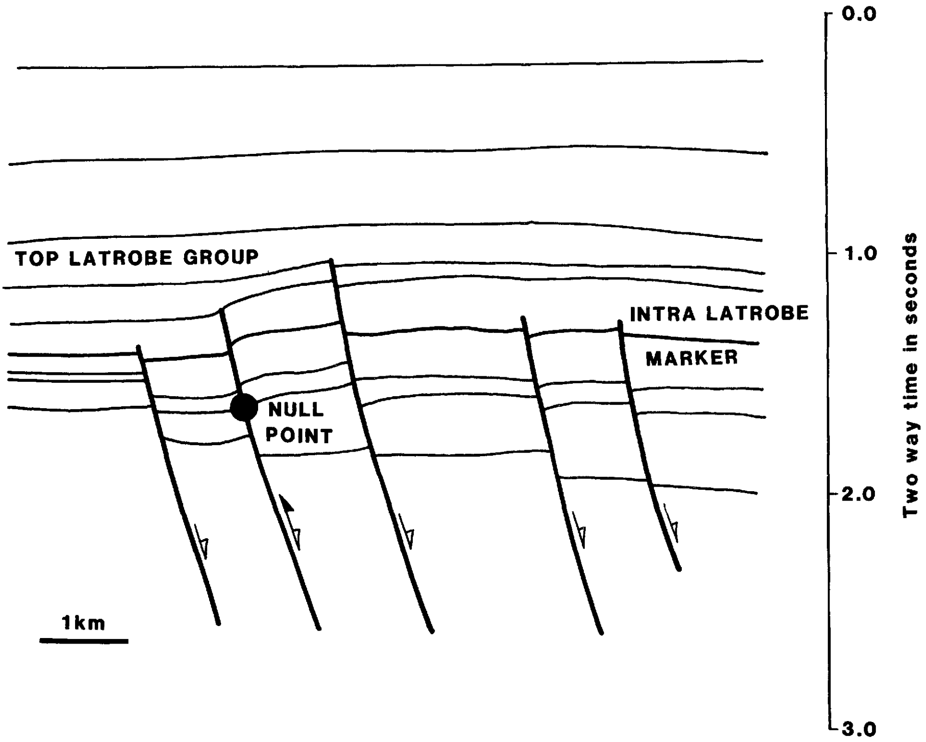


FIG. 9. Line drawing of an interpreted seismic section across the Snapper Field, Gippsland Basin, SE Australia (after Davis 1983).

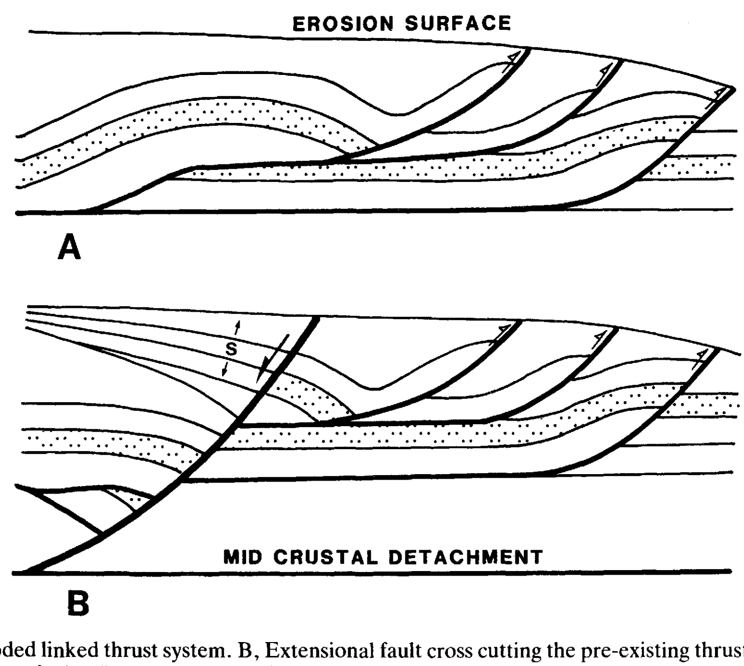


FIG. 10. A, Eroded linked thrust system. B, Extensional fault cross cutting the pre-existing thrust system with no re-use of thrust faults. S represents a synrift extensional sequence.

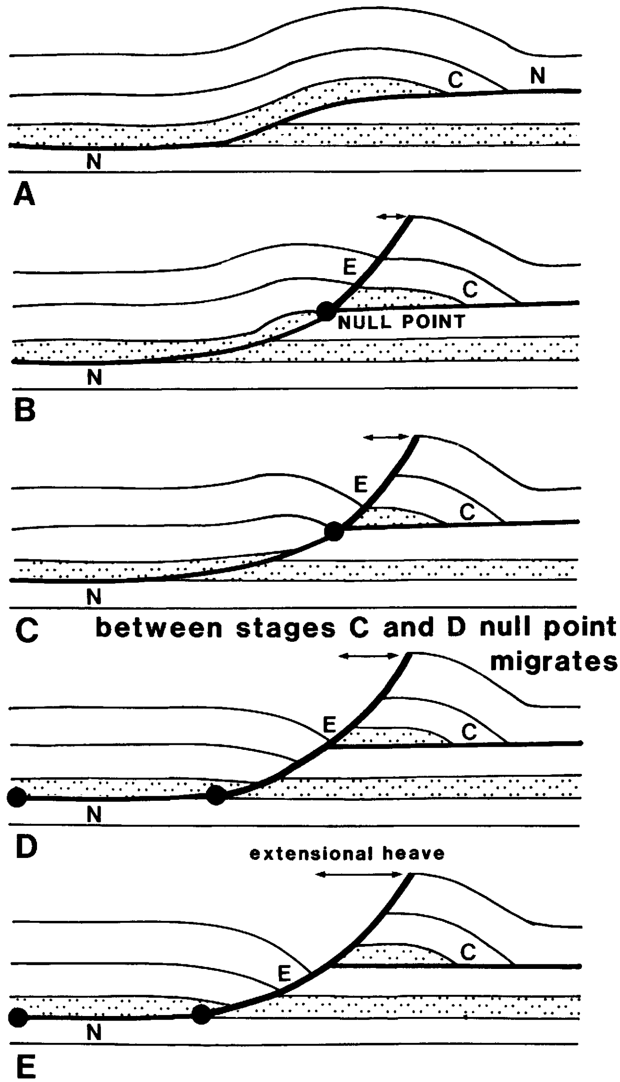


FIG. 11. Sequential diagrams to show the shortcutting and partial reactivation of a single thrust fault by extensional movements. Faults are labelled C, contractional; N, neutral; and E; extensional (represented by thicker lines).

system would be represented by extensional and neutral faults with only the shortcut remnant of thrust 2 showing net contraction.

Recognizing inversion on geological maps

The recognition of inversion tectonics and the quantification of inversion ratio may be performed using geological maps where structures have some degree of plunge. A good stratigraphic control is essential. A region that has undergone positive inversion of a synrift (extensional) stratigraphy will contain faults that apparently change from normal to reverse across the map. In the simplest case, an extensional fault displaces younger material in its hanging wall above older rocks in its footwall. A contractional fault displaces older material on younger rocks. Considerations of net slip are unimportant. A simplified geological map of the Weymouth District (BGS 19) illustrates the

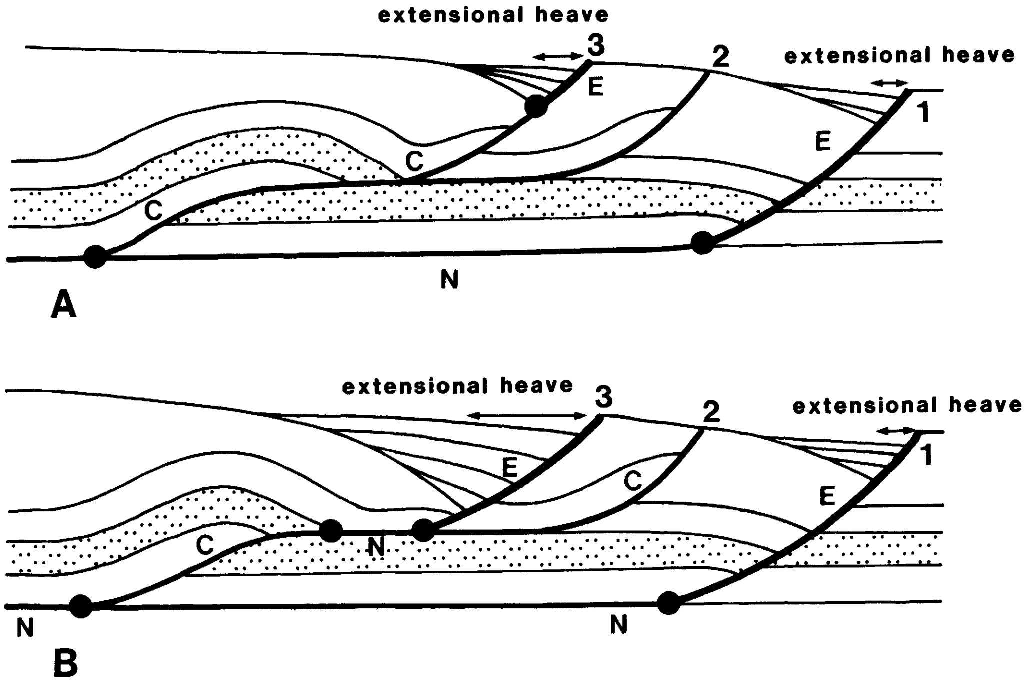


FIG. 12. Thrust system as in Fig. 10, partially reactivated in extension. A and B show two stages in reactivation. Faults are labelled C, contractional; N, neutral, and E, extensional (represented by thicker lines).

concept of changing mode along a single fault (Fig. 13). This effect results from positive inversion tectonics. In this region, the Jurassic and Lower Cretaceous sequences are considered to be synrift. The Upper Cretaceous is a postrift sequence deposited above a significant unconformity (Stoneley 1982). The point of change along the fault from net normal to net reverse displacement is the null point. In this case it occurs at the Upper Cretaceous unconformity.

The geometry of inversion may be analysed and the inversion ratio may be calculated using stratigraphic separation diagrams (Elliott & Johnson 1980) for individual faults. Stratigraphic separation is the displacement of a stratigraphic marker by a fault. Displacement is measured perpendicular to bedding. Stratigraphic separation may be measured in map view along a fault at positions of known stratigraphy. Curves of hanging wall and footwall stratigraphy cut by the fault may be plotted against fault map length. In normal faults, the hanging wall curve plots above that of the footwall. In reverse faults the footwall curve plots above that of the hanging wall. Where footwall and hanging wall stratigraphy differs, both stratigraphic sequences may be incorporated in the stratigraphic separation diagram by plotting individual curves using the appropriate stratigraphy (Fig. 10).

Where faults have undergone positive inversion, the curves cross at the null point. Using the hanging wall synrift stratigraphy, parameters d_h, d_e and d_c may be measured for use in equations (2) and (3) for the calculation of inversion ratio. However, this is not possible in the Weymouth example (Fig. 10) because of erosion and partial omission of Jurassic and Lower Cretaceous stratigraphy in the fault hanging walls. A phase of contractional inversion coupled with erosion took place before the deposition of the Upper Cretaceous/Tertiary section.

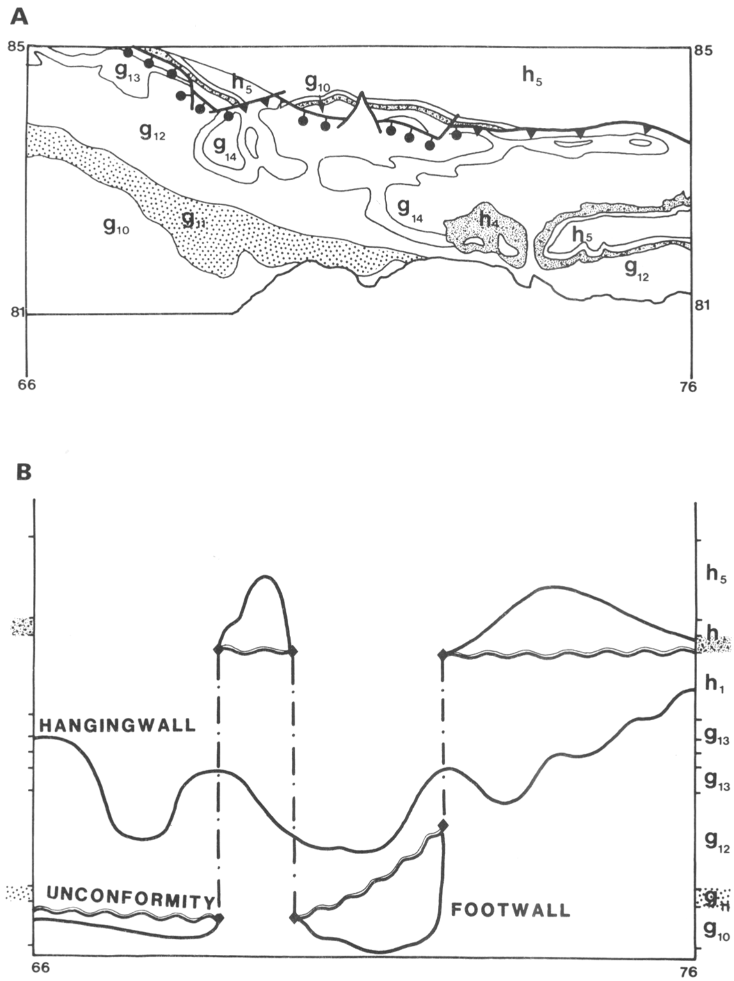


Fig. 13. A, Simplified geological map of the area N of Weymouth (from BGS sheet Weymouth) to show switching in fault mode from normal to reverse as a result of positive inversion. ▼▼, reverse fault; ●●, normal faults. B, Stratigraphic separation diagram constructed from Weymouth sheet. Note that this diagram is plotted on a full stratigraphic frame. Certain parts of the Jurassic/Lower Cretaceous stratigraphy is missing below the Albian (h4) unconformity as a result of early contractional inversion coupled with erosion. The missing stratigraphy is represented by dashed lines in the foot wall curve.

References and further reading

Beach, A. 1984. Structural evolution of the Witch Ground Graben. *Journal of the Geological Society of London*, **141**, 621–628.

Davis, P. N. 1983. Gippsland Basin, SE Australia. *In*: Bally, A. W. (ed.) *Seismic Expression of Structural Styles. American Association of Petrology Geologists Special Publication*, **3**, 3.3.19–3.3.24.

Elliott, D. & Johnson, M. R. W. 1980. Structural evolution in the northern part of the Moine Thrust Belt, Northwest Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **71**, 69–96.

Gibbs, A. D. 1984. Structural evolution of extensional basin margins. *Journal of the Geological Society of London*, **141**, 609–619.

Glennie, K. W. & Boegner, P. L. E. 1981. Sole Pit inversion tectonics. *In*: Illing, L. V. & Hobson, G. D. (eds) *Petroleum Geology of the Continental Shelf of NW Europe*. Institute of Petroleum, London, pp. 110–120.

Hamblin, W. K. 1965. Origin of "reverse drag" on the downthrown side of normal faults. *Geological Society of America Bulletin*, **76**, 1145–1164.

STONELEY, R. 1982. The structural development of the Wessex Basin. *Journal of the Geological Society of London*, **139**, 545–554.

WILLIAMS, G. D. and CHAPMAN, T. J. 1983. Strains developed in the hanging walls of thrusts due to their slip/propagation rate: a dislocation mode. *Journal of Structural Geology*, **5**, 563–571.

G. D. WILLIAMS & C. M. POWELL, Department of Geology, University of Keele, Keele, Staffordshire, ST5 5BG, UK.

M. A. COOPER, BP Canada Inc., Oil and Gas Division, 333 Fifth Avenue SW, Calgary, Alberta T2P 3B6, Canada.