Pergamon

Journal of Structural Geology, Vol. 19, No. 5, pp. 719 to 734, 1997

0191-8141/97 $17.00+0.00

PII: S0191-8141(96)00114-9

Structure of the Alice anticline, Papua New Guinea: serial balanced cross-sections and their restoration

R. A. MASON*

Department of Geology, Royal School of Mines, Imperial College of Science, Technology and Medicine, Prince Consort Road, London SW7 2BP, U.K.

(*Received* 14 *August* 1995; *accepted in revised form* 21 *November* 1996)

Abstract—The structure of the western part of the Papuan Fold Belt is characterised by both thin-skinned thrusting and basement involved structures. Basement involvement is attributed to inversion of earlier formed extensional faults. The Alice anticline is a frontal structure of the Papuan Fold Belt and formed due to inversion of a Tertiary extensional fault system.

Complex forelimb geometry of the Alice anticline changes markedly along strike and suggests varying amounts of shortening in this part of the structure. Balanced cross-sections quantify differential shortening along the anticline, whereas palinspastic restoration shows that the differential shortening is compatible between cross-sections.

Three-dimensional restoration of the Alice anticline makes use of a series of balanced cross-sections and is based on a line-length method. Paradoxically, the restoration reveals non-plane strain in the balanced cross-sections upon which it relies. However, the restoration also reveals and quantifies a component of rotation about vertical axes which would not be detected by application of conventional methods of structural analysis.

Rotations about vertical axes are attributed to pinning of progressive, foreland propagating deformation. The distribution of rotations about vertical axes suggest that zones of pinning are coincident with relay zones in the early extensional fault geometry. Two relay zones associated with the original geometry acted as obstructions to deformation and have effectively pinned contractional structures during their formation causing the rotations about vertical axes. Such rotations are not manifested in changing fold axis orientations and have only been derived from a consideration of material balance during deformation. © 1997 Elsevier Science Ltd.

INTRODUCTION

Cross-section balancing has been used widely to produce structural models of the external parts of fold and thrust belts and is commonly used in both contractional and extensional tectonic settings. The basic principles have been outlined by Dahlstrom (1969), Hossack (1979), Boyer and Elliott (1982), Gibbs (1983), Woodward *et al.* (1985) and De Paor (1988a,b). However, attempts at three-dimensional balancing and restoration are much less common and the methods vary.

Three-dimensional restoration is a term used here to describe the restoration of a curved surface in 3-D space to its pre-contractional deformation state. It is not meant to imply three-dimensional balancing, which must account for volume changes in the deformed and restored states, although it could be a first step in such a process. Incorporation of three-dimensional data into balancing techniques have been designed primarily to help understand the kinematic evolution of a region or structure. For example, Enfield and Coward (1987) employed a three-dimensional restoration technique for the West Orkney Basin, Scotland, to derive principal axes of bulk strain associated with extension. Laubscher (1987) used a block mosaic model to constrain Neogene movements in the northern Andes. This method was employed more quantitatively by Bitterli (1990) to model the three-dimensional kinematic evolution of the Weissenstein anticline in the Jura Mountains.

The aims of this paper are two-fold. Firstly, a new but simple method is demonstrated for incorporating three-dimensional data as an additional constraint to construction of balanced cross-sections. Secondly, a model for the structural evolution of the Alice anticline as derived from serial balanced cross-sections is presented. The model is constrained by, and is used to demonstrate, the three-dimensional technique and represents the first such model for the westernmost part of the Papuan Fold Belt in Papua New Guinea. Data come from field mapping and conventional structural analysis.

REGIONAL SETTING

New Guinea forms the deformed northern margin of the Australian plate. Tectonics in the south-western Pacific since the Triassic have resulted in the present configuration of geological provinces and accreted terranes (Pigram and Davies, 1987). From south to north New Guinea consists of undeformed Australian cratonic foreland, a deformed fold belt including unmetamorphosed and, generally, weakly metamorphosed rocks which are bounded to the north by volcanic and metamorphic rocks of the New Guinea Mobile Belt (Dow, 1977). The Papuan Fold Belt (Dow, 1977) is located within Papua New Guinea, the eastern half of New Guinea (Fig. 1), and comprises deformed basement,

*Present address: Australian Geodynamics Cooperative Research Centre, C.S.I.R.O. Exploration and Mining, PO Box 437, Nedlands, WA 6009, Australia.

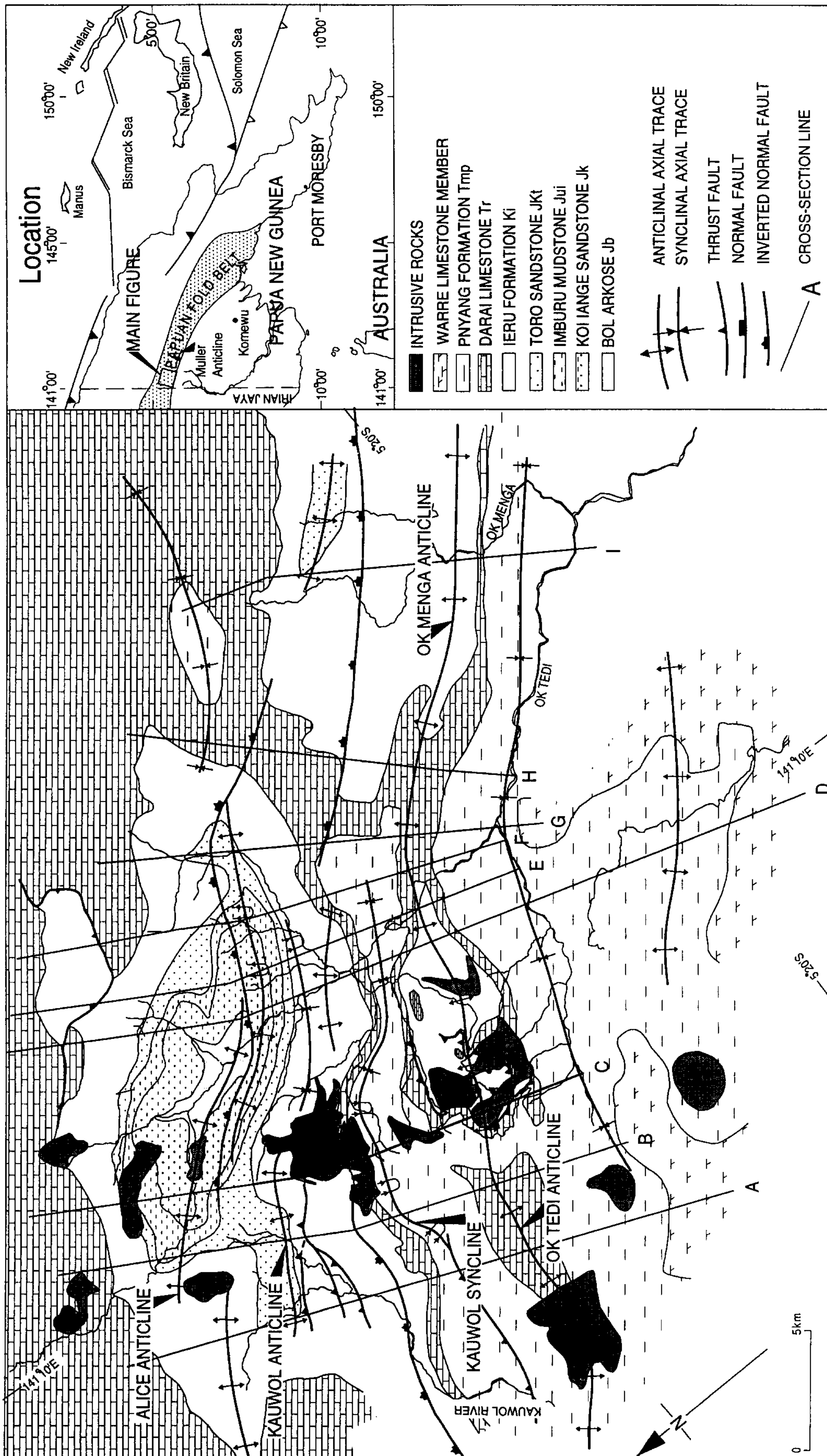

Fig. 1. The study area. Inset shows simplified tectonic map of Papua New Guinea and location. Main figure shows study area geology, cross-section location and stratigraphy. Note the locations of Komewu and the Muller anticline on the location map.

platformal and basinal Mesozoic sediments, and Tertiary carbonate and clastic sediments of the Papuan Basin. Compressional deformation within the fold belt began possibly as early as Middle to Late Miocene (Mason, 1994) and is continuing as evidenced by current seismicity (Cooper and Taylor, 1987).

The Papuan Basin evolved on the passive northern margin of the Australian Plate from the Triassic until the early Tertiary. Triassic sediments in the northern part of the Papuan Fold Belt (Kubor Block) have been attributed to the onset of rifting (Davies, 1990). Home *et al.* (1990) reported the occurrence of Triassic volcaniclastics and associated sediments in this area and suggest they record the earliest deposition within the Papuan Basin. Their considerable thickness (up to 3500 m) and rapid thickness changes suggests a syn-rift origin (Home *et al.*, 1990). These sediments have no equivalents further south (Burns and Bein, 1980) as the sedimentary section thins away from the basin depocentre (Davies, 1990). The Mid-Jurassic and Cretaceous section is attributed to a post-rift thermal subsidence phase (Home *et al.*, 1990). Back-arc extension during the Oligocene to Early Miocene (Smith, 1990) is reflected by the deposition of the Darai limestone and clastic sedimentation to the north and to the east, in the Aure Trough (Home *et al.*, 1990). Compressional deformation, attributed to volcanic arc collision in northern Papua New Guinea, occurred possibly in the Late Miocene (Jaques and Robinson, 1977; Smith, 1990; Home *et al.*, 1990). This change to compressional tectonics is recorded by deposition of a Pliocene foreland basin sequence (Home *et al.*, 1990) south of the present day mountain front and is also reflected in apatite fission track analysis uplift dates (Hill and Gleadow, 1989).

Extensional, syn-sedimentary faults are common in sedimentary basins and their thrust reactivation, or inversion (see Williams *et al.*, 1989), commonly accompanies intra-continental deformation (Coward, 1994). Syn-sedimentary faults are preserved in the undeformed foreland part of the Papuan Basin and their inversion has been inferred within the deformed parts in the Papuan Fold Belt. Hill (1989) attributed formation of the Muller anticline to reverse movement on pre-existing northeast- and southwest-dipping extensional faults. A normal fault, outlined by exploration wells, has been identified in the undeformed foreland (Komewu area, Hill, 1991). This fault dips to the north and is accompanied by a considerable change in thickness of the Mesozoic sedimentary section. Hill (1991) proposes an interpretation in which the thickness change occurs in both the Miocene limestone and the Mesozoic sedimentary section. South of the Alice anticline the presence of north-dipping extensional faults is clear on seismic reflection profiles in the undeformed foreland area (Texaco, 1972). One of these coincides with a marked thickness change in the Oligocene–Miocene Darai limestone suggesting growth at this time.

The faults described above may be interpreted as being active normal faults during either the Mesozoic, the Mesozoic and the early Tertiary, or the early Tertiary only. This is consistent with an interpretation of Triassic to possibly earliest Jurassic rifting followed by post-rift thermal subsidence until renewed extension in the early Tertiary. Hill (1989, 1991) has interpreted the inversion of such extensional faults as having formed the large, basement-cored anticlines (including the Muller anticline) near the frontal part of the fold belt.

STRUCTURE OF THE ALICE ANTICLINE

The Alice anticline (Fig. 1) occurs within the frontal zone of the fold belt. Off-set and curvilinear fold axial traces are characteristic of the Alice anticline in the study area and suggest non-plane strain.

The area considered in this study extends south from the Alice anticline to the essentially undeformed foreland (Fig. 1). It comprises several structures, the largest being the Alice anticline which exposes the lower part of the Tertiary sedimentary section and almost the entire Mesozoic sedimentary section. The structures in this area generally verge to the south which is compatible with the southward-directed thrusting north of the Alice anticline area and in other areas of the Papuan Fold Belt (Davies and Norvick, 1974; Jenkins, 1974; Hobson, 1986; Hill, 1989, 1991; Mason, 1994).

The Mesozoic section is exposed down to the lowest unit, the Bol arkose, on the generally gently dipping, unfaulted northern limb of the Alice anticline (Fig. 1). Because the base of the sedimentary section is not exposed, the total thickness is unknown, although its minimum thickness is ca 300 m. Estimated thicknesses from other areas range from 0 to 1650 m (Hill, 1989). An approximate thickness of 900 m has been assumed for this area. The Bol arkose is not exposed on the southern, steeply dipping limb, so that its thickness south of the Alice anticline cannot be constrained. Other overlying Mesozoic units maintain constant thickness across the Alice anticline and hence it is assumed that the Bol arkose remains constant in thickness although it is recognised that this assumption may be incorrect.

In contrast, the Darai limestone, the lowest part of the Tertiary sedimentary section, clearly does not maintain constant thickness across the Alice anticline. The thickness of the Darai limestone reaches 1000 m in cliff exposures north of the anticline whereas, on the southern limb, several exposures confirm a thickness of 250–300 m. On both sides of the anticline the limestone is generally of the same appearance, that is, massive to bedded on a decimetric scale with common foraminfera and shell fragments and has been interpreted as a shallow carbonate platform facies (Arnold *et al.*, 1979). Ages of the Darai limestone are similar for both sides of the anticline and are generally in the range Late Oligocene to Middle Miocene (Davies and Norvick, 1974; Arnold *et al.*, 1979; Haig *et al.*, 1990)

In detail, the anticline is not a simple structure but consists of several folds and thrusts in the (southern) forelimb. The position of the thrusts and their amount of slip determines the detailed geometry of the forelimb of the anticline which changes markedly along strike. The forelimb contains maximum bedding dips ranging from 20° (right way up) to strongly overturned in some parts of the anticline. In contrast, the crest is generally flat lying and the north limb gently to moderately dipping.

South of the Alice anticline is the Ok Tedi anticline, which to the east becomes the Ok Menga anticline. The Ok Tedi anticline is separated from the Alice anticline by the Kauwol syncline (Fig. 1). These anticlines are smaller than the Alice anticline and only expose the Cretaceous Ieru Formation rather than the entire Mesozoic section. A frontal syncline, south of the Ok Tedi and Ok Menga anticlines (Fig. 1), essentially returns stratigraphy back to its undeformed regional level in the foreland.

Balanced cross-sections

Sufficient outcrop of reasonable quality has enabled the construction of nine balanced cross-sections through the Alice anticline area (Fig. 2). These form the basis for the three-dimensional restoration and analysis. Some are intermediate cross-sections in areas of poor outcrop and are considered to be constrained adequately by projection of structures from adjacent cross-sections and well-constrained map outcrop patterns. Structures at depth are constrained only by the geology exposed at the surface and the requirement that cross-sections balance and are restorable in three dimensions.

Construction of balanced cross-sections requires that potential sources of strain not described by the large-scale geometry (i.e. internal strain which may include features such as cleavage, joints and small scale structures) are considered in areas of penetratively deformed rocks. However, joints and veins appear to accommodate only very small strains (e.g. Reches, 1976). In the Alice anticline area no fabric is developed and the only mesoscopic structures observed are joints, veins and relatively rare minor fold and fault structures. Another source of strain in rocks which are not penetratively deformed is due to stretching associated with non-cylindrical folding. If folding deviates from isometric bending (Lisle, 1992), then it does not strictly maintain constant bed length in three dimensions. The amount of bedding curvature parallel to the fold axes in the study area is much smaller than that orthogonal to the fold axes so that such strains are likely to be very small. Lack of penetrative structures is consistent with strain accommodation by bending at fold hinges, simple shear on fold limbs and displacement on faults. It is assumed therefore that deformation in the study area is adequately recorded by large-scale folds and faults with little internal strain of beds and the construction of balanced cross-sections is considered valid.

Balancing the cross-sections that cut the Alice anticline and maintaining mapped and inferred thickness distributions of the sedimentary units indicates that some of the faults present may have been pre-existing extensional faults which have been inverted during contractional deformation. In particular, the thickness change in Darai limestone across the Alice anticline is interpreted to result from extensional fault movement in the early Tertiary, during limestone deposition. Constant thickness of Mesozoic units, except perhaps the Bol arkose, indicates that the extensional fault formed and was active only in the early Tertiary. The southward vergence of the Alice anticline and the increased thickness of Darai limestone to the north (see Fig. 2) together with a north-dipping fault identified by mapping suggest that the interpreted extensional fault dipped to the north.

The Kauwol and Ok Menga anticlines are offset from the Alice anticline and for the reasons outlined above (for the Alice anticline) are also interpreted to be due to inversion of a Tertiary extensional fault (Fig. 3). The Ok Menga anticline is an along strike continuation of the Ok Tedi anticline but the underlying structure changes through a zone where the Ok Tedi anticline becomes a broad flexure (cross-sections G and H, Fig. 2). The regions between the Kauwol, Alice and Ok Menga anticlines are further interpreted as relay zones in the original geometry of the extensional fault system, the tip lines of which appear to control fold terminations (Fig. 3).

The smaller scale anticlines observed to the south of the Alice anticline suggest an interpretation which incorporates detachment levels higher in the section than that responsible for the formation of the Alice anticline. Accordingly, underlying thrust faults have been interpreted at or near the base of the Cretaceous Ieru Formation (Fig. 2). These emanate from the inverted extensional fault as footwall shortcut faults (e.g. Coward *et al.*, 1991). Similar interpretations regarding detachment levels within the Ieru Formation have been made in other areas of the fold belt (Lamerson, 1990). The Ok Tedi anticline is therefore linked to the Alice anticline by a detachment near or at the base of the Ieru Formation and has formed due to thrusts and back thrusts splaying off this detachment. The interpretation of the underlying structure of the Ok Tedi anticline is characterised by blind thrusts and fault-propagation folds that tip below the surface within the Ieru Formation which, as a result, has been area balanced.

Distribution of bulk shortening

Bulk shortening is calculated as the percentage change in distance between the pin line and the loose line from the deformed state to the restored state. The cross-sections shown in Fig. 2 extend to the effectively undeformed foreland and therefore have been pinned as close to this as practicable. Where pinning at the undeformed foreland has not been possible, the axial surface of an open, frontal syncline has been used. Because no single structure continues along strike it is

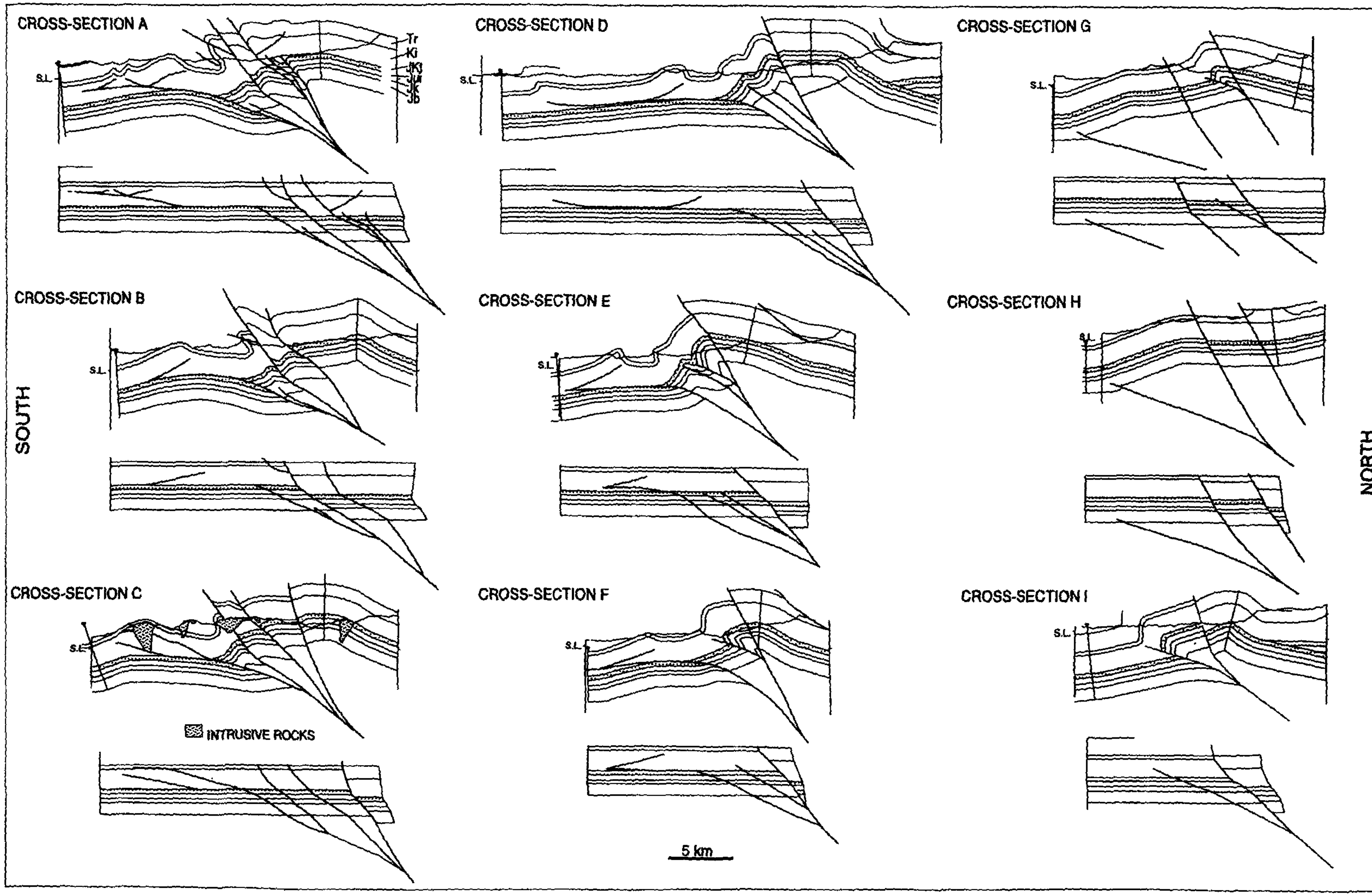

Fig. 2. Balanced cross-sections A–I showing both deformed and restored state sections. Note thickness change in Darai limestone (Tr) across inverted extensional fault. Deformation south of the inverted extensional fault is interpreted to be related to a detachment near the base of the Cretaceous Ieru Formation (Ki). Bulk shortening calculated by the change in distance between the pin lines and loose lines from the deformed to the restored states at Toro sandstone (shaded) level is as follows: A 25.2%, B 21.1%, C 19.4%, D 14.7%, E 22.7%, F 19.7%, G 9.3%, H 5.2% and I 23.4% (qualitative comparison of bulk shortening estimates is discussed in the text). Restored cross-sections are only drawn between the pin line and the loose line while deformed-state cross-sections include more of the section than is actually restored.

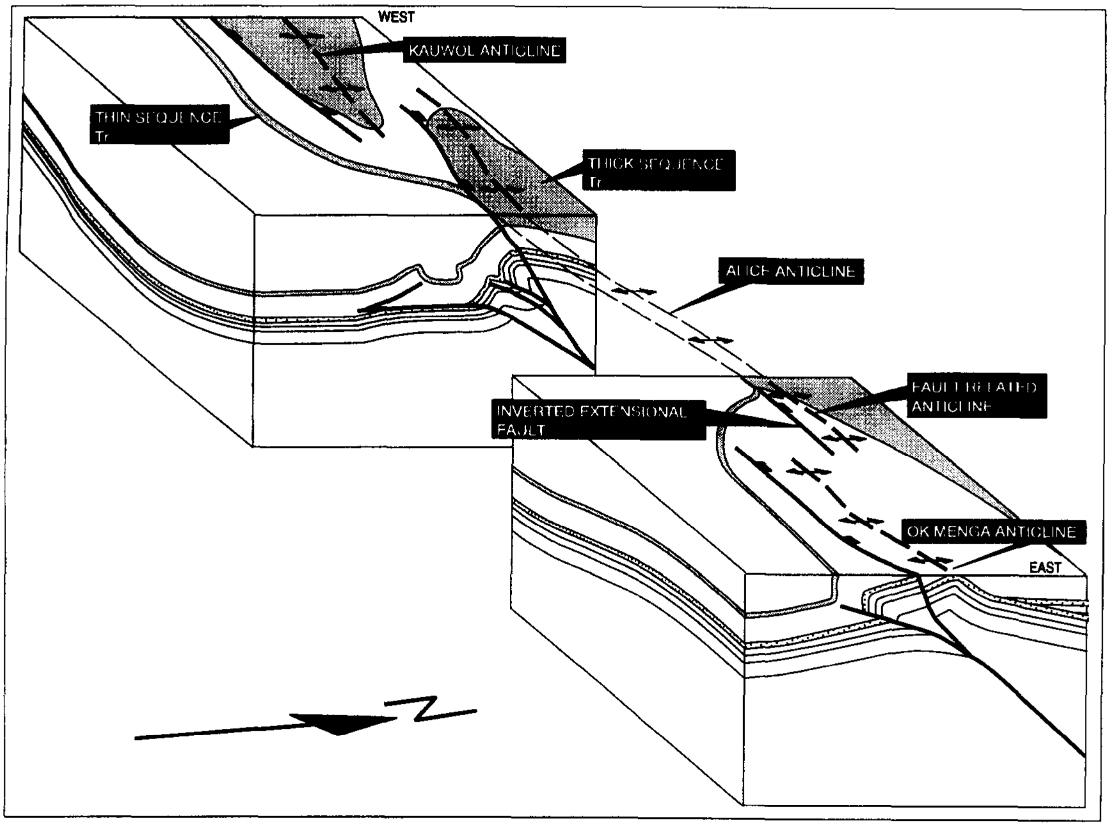

Fig. 3. Simplified block diagram of structure of the Alice anticline area. The distribution of anticlinal axial traces is interpreted to reflect the positions of inverted extensional faults.

difficult to place loose lines in equivalent structural positions thus allowing comparison of bulk shortening estimates. As an approximation, loose lines have been placed as near as practicable to the axial surface of the Alice anticline or its equivalents (the Kauwol and Ok Menga anticlines). While this positioning of loose lines attempts to satisfy the constraint of no interbed slip it does not allow a quantitative comparison of bulk shortening estimates. Despite this, bulk shortening variation along strike is indicated, both by the calculated bulk shortening for each cross-section (Fig. 2) and by the intensity of folding and faulting on each section. A qualitative analysis is therefore possible.

Increased bulk shortening towards the west from cross-section D through to cross-section A is accommodated by increased slip on the lowest footwall shortcut fault which is distributed through the Ieru Formation (unit Ki in Fig. 2) via a detachment near its base. This results in a slight increase in size of the Ok Tedi anticline and development of subsidiary structures shown in cross-section A. This shortening is matched by shortening within the Darai limestone by increased overturning of the northern limb of the Kauwol syncline. Above and to the north of the lowest footwall short cut fault are several thrusts that die out to the east and so contribute to this decreased shortening. The two northernmost thrusts on cross-section A splay off the major thrust through its hangingwall sequence and contribute to the increased shortening from cross-section B to cross-section A.

Bulk shortening increases slightly to the east from cross-section D to E then diminishes further westward to cross-section H. Reduced bulk shortening between cross-sections E and H is manifested by decreased inversion of the normal fault and a concomitant decrease in size of the Alice anticline which terminates completely between cross-sections G and H. Between cross-section H and I bulk shortening increases due to inversion of an eastern segment of the extensional fault. The area of reduced shortening shown by cross-section H coincides with a change in strike (see Fig. 1) and to a change in underlying structure between the Ok Tedi anticline and the Ok Menga anticline.

Each cross-section shows similar structural style and many structures can be traced from one section to another. The loss of some structures from section to section can generally be rationalised in terms of changes in bulk shortening. To test the compatibility of the differential shortening between sections, footwall cut-offs have been restored in map view (Fig. 4). This restoration has been carried out by bed line-length restoration along the cross-sections at the top of the Toro sandstone (unit Jkt in Fig. 2).

Restoring footwall cut-offs, or any other features, along section lines assumes plane strain conditions

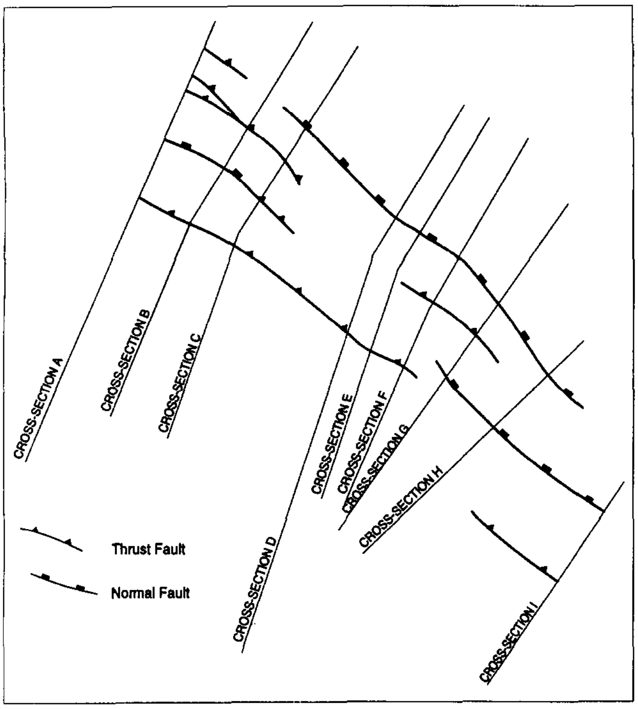

Fig. 4. Restored footwall cut-offs for the top of the Toro sandstone. Restoration is by line length along cross-section lines, and therefore assumes plane strain deformation. This restoration is used for initial assessment of the compatibility of differential shortening between cross-sections.

which may not be the case for the Alice anticline. However, as a first approximation for assessing the degree of compatibility of differential shortening between cross-sections, this type of restoration is considered useful. All faults restore to reasonable geometries in map view so that the different amounts of shortening incorporated in each section are compatible despite their apparently large variation.

THREE-DIMENSIONAL RESTORATION

Differential shortening is most notably manifested by along-strike variation in the geometry of the forelimb of the Alice anticline. If differential shortening between cross-sections is not accommodated by section-parallel, simple shear strains (e.g. Enfield and Coward, 1987), it must involve non-plane strain and therefore questions the validity of constructing balanced cross-sections through the area. However, balanced cross-sections together with a three-dimensional restoration, further constrain the interpretation of the structure. In addition, the three-dimensional restoration may provide information on the movement of material during deformation.

It is assumed, in cross-section balancing, that bed lengths are the same in the deformed state as in the restored state. Likewise, the same assumption should be valid for bed lengths measured in any direction on any part of a bedding surface curved in three dimensions. That is, any point on a bedding surface is 'tied' to adjacent points by finite bed lengths and, given that there is no internal strain, then these points, at any stage of the deformation, remain at fixed distances from one another as measured in the curved bedding surface. If, in order to accomplish the deformation specified by the geometry of mapped and interpreted structures, these bed lengths cannot remain constant, then the deformation must involve an internal strain, which beyond a certain value will be observable in the field as a micro-structure or fabric. In cases where cleavages are developed, strain data should be incorporated into balanced sections (Woodward *et al.*, 1985) and into any three-dimensional restoration. Another problem arises when the deformation is discontinuous as is largely the case in foreland thrust belts. Again, assuming no internal strain, bed lengths remain fixed but adjacent points may be separated by a fault. In this case the points are tied respectively to the hangingwall and footwall by finite bed lengths and, assuming dip-slip displacement on the fault, can be matched up across the fault upon restoration.

Methodology

The restoration described here involves restoring a set of points on a bedding surface curved in three dimensions. In this case the top of the Toro sandstone has been chosen as the horizon to be restored. The Toro sandstone is a competent sandstone unit and represents a key bed as defined by Mitra and Namson (1989). To facilitate visualisation of the effects of restoration and to appreciate the movement of points on the restored horizon, a set of parallel lines spaced 2 km apart has been constructed over the map of the study area (Fig. 5). The orientation of these lines was chosen to approximate the average strike

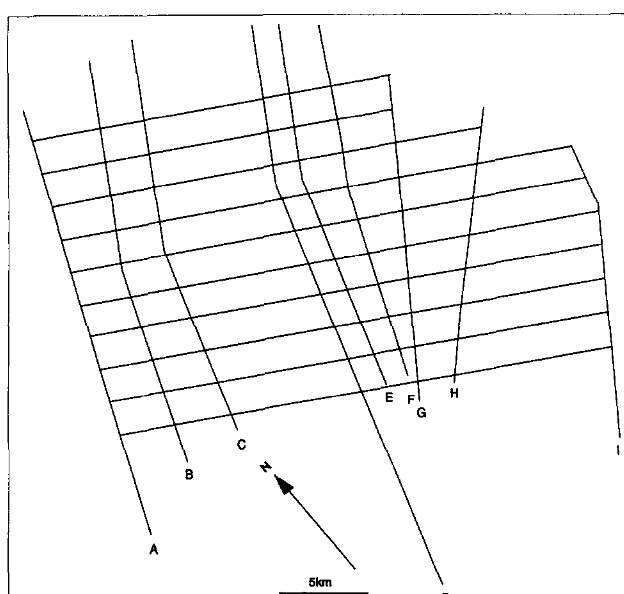

Fig. 5. Balanced cross-section lines A–I as shown (Fig. 1) showing positioning of 2-km spaced parallel lines which, together with the cross-section lines, form a grid whose intersection points have been restored with respect to the top of the Toro sandstone (JKt).

of structures across the study area and when combined with the cross-section lines forms a grid. Lengths of lines forming the grid have no real significance; their purpose is to define a set of regularly spaced (in one direction, at least) points at the intersections of the grid lines. It is the position of these points in the deformed state compared to their position in the restored state that is of particular interest. The points of intersection of grid lines have been vertically projected to intersect the top of the Toro sandstone (Fig. 6) and form a set of passive marker points which, because they are used to analyse the deformation in the same way as loose lines on a balanced cross-section (Geiser, 1988), are termed loose points.

To restore loose points from the balanced cross-sections it is simply a case of measuring bed lengths between loose points as for a typical line-length restoration of a balanced cross-section. To facilitate restoration of loose points in the third dimension, vertical cross-sections have been constructed along the average strike lines (Fig. 7). Similarly, bed lengths between adjacent balanced cross-sections may be measured using these along-strike cross-sections.

Bed line-lengths are now specified between each loose point and the three-dimensional restoration can be carried out. For an area-constant restoration, the bedding surface area defined by a grid block, whose vertices are four loose points and whose sides are defined by bed lengths which tie the loose points, must remain the same in the deformed state as in the restored state. However, given the difficulty in measuring the area of a bedding surface which is curved in three dimensions (i.e. non-developable, see Lisle, 1992), the only consideration given to block areas in this restoration is that blocks, upon restoration, should be kept at maximum area. This is because any block in the deformed or the restored state is only represented by the lengths of lines defined by the intersection of the bedding surface and the cross-sections. These intersections form the boundary of a block and when unfolded (straightened) during restoration will not account for any contribution to the area of a grid block by non-developable curvature. Such curvature will contribute to a slightly greater area than can be represented by the four straightened lengths of its boundary. Errors of this type can be minimised by reducing the grid size relative to the curvature such that the true curvature is adequately represented by a series of flat panels. The bedding surface area of a block in the deformed state will therefore represent the minimum bedding surface area (for contractional deformation, Fig. 8). Any admissible restoration should have the same total area in both the restored and deformed state models.

In the same way that a balanced cross-section is pinned for restoration so must a restoration in map view be pinned. The structure of the Alice anticline has been assumed to have formed in a foreland propagating sequence as is common for many fold and thrust belts. As a consequence, structures have been restored in the reverse order to that in which they formed from a pin line located in the foreland. Except where stated, restorations are pinned along the southernmost loose point line (located furthest towards the foreland) as it is assumed (as for balanced cross-sections) that this will most closely approximate the condition of no interbed slip and that structures developed in a foreland propagating sequence. However, another pin line is required which represents a datum in the same way that the horizontal represents a datum to which bedding can be restored on a cross-section. The choice of a datum pin line will affect the movement of loose points and different choices in datum pin line will result in different restorations.

Figure 9(a & b) show restorations which have been pinned along the foreland loose point line and all bed line

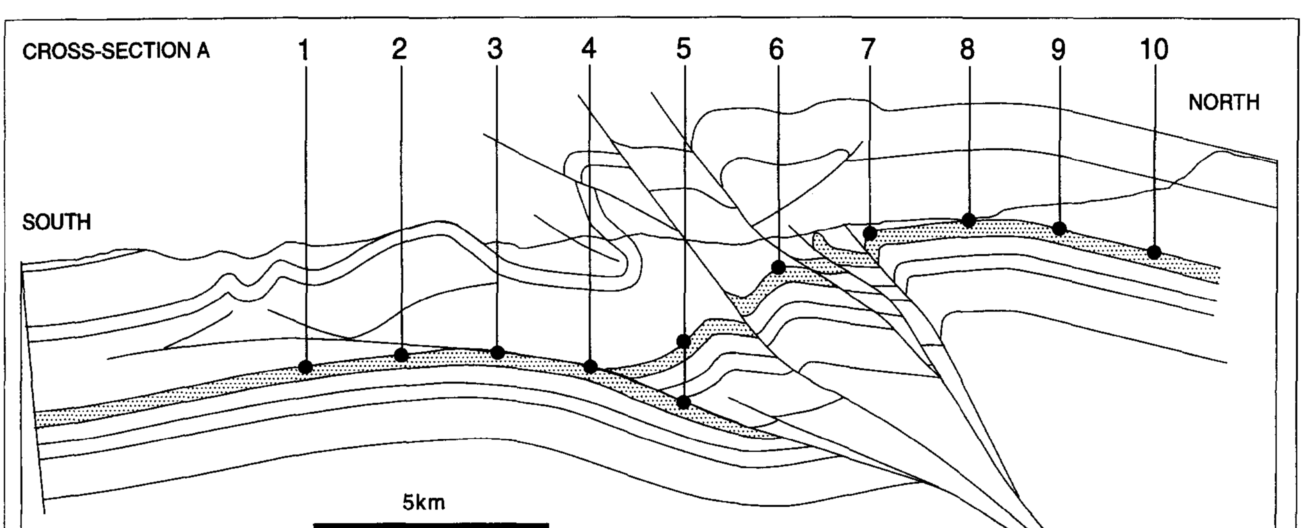

Fig. 6. Cross-section A showing definition of loose points by projection from surface of grid line intersection points. Note that projection line 5 intersects the top of the Toro sandstone twice due to a thrust repeat of this horizon.

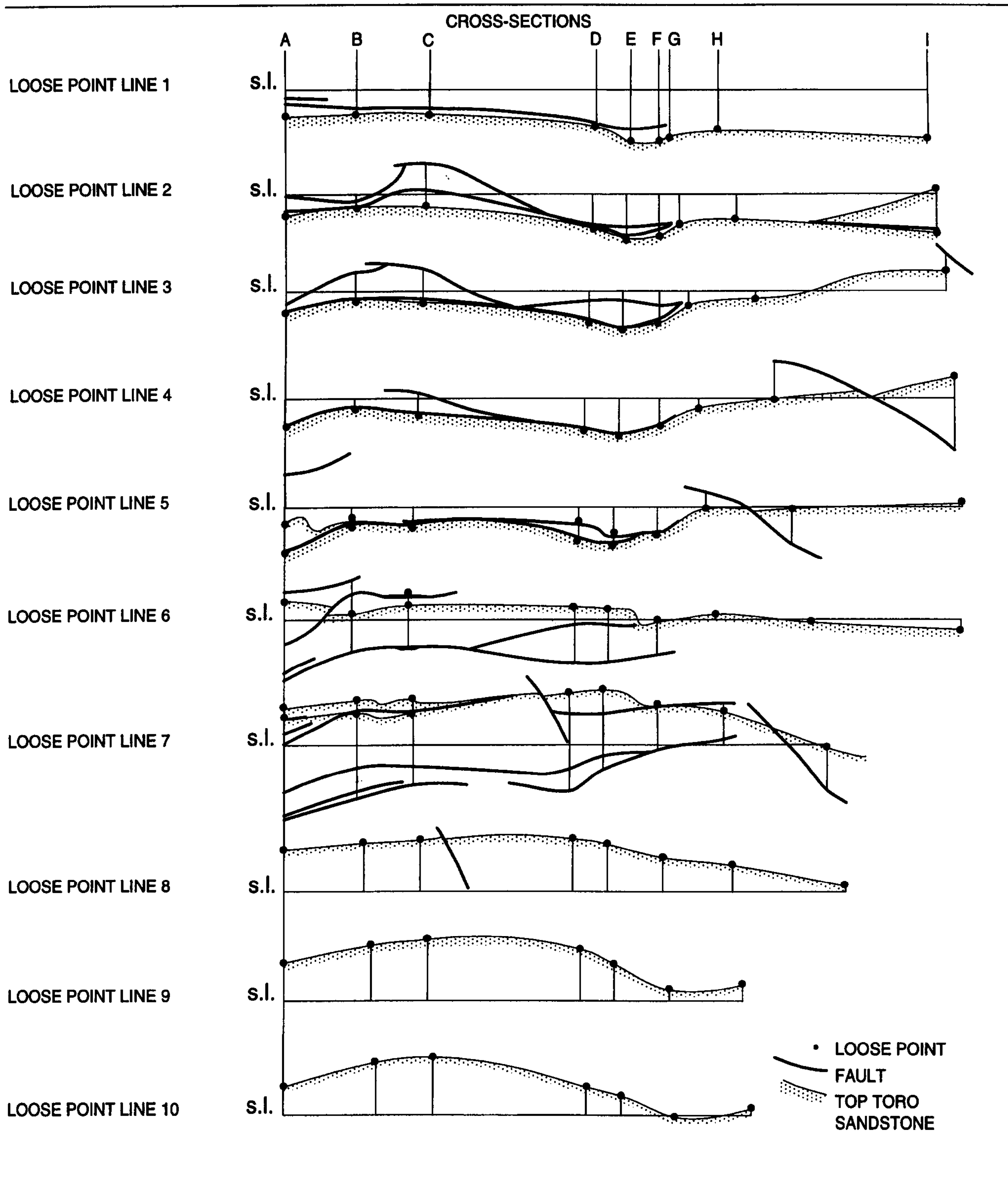

Fig. 7. Loose point line cross-sections as defined (see text and Fig. 4). These cross-sections are approximately parallel to the average strike of structures in the area and have been constructed in order to measure bed lengths between adjacent balanced cross-sections, A–I. The vertical projection of grid intersection points (loose points) are shown.

lengths connecting loose points are matched up across faults. That is, dip-slip displacement on all faults is assumed. These two restorations have datum pin lines at the western most cross-section (cross-section A, Fig. 9a) and at the eastern most cross-section (cross-section I, Fig. 9b). In theory any number of viable restorations may be constructed and it may be necessary to choose the restoration most likely to be correct based on other

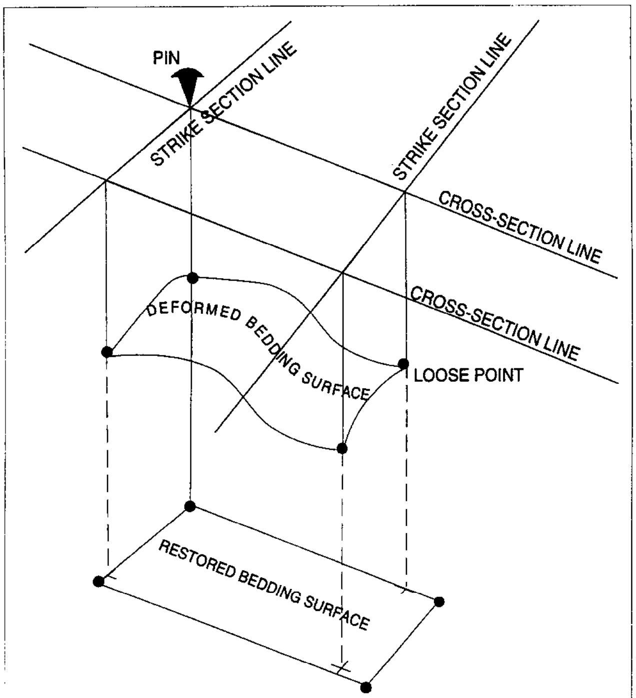

Fig. 8. The area defined by a restored grid block is a minimum of possible bedding surface area since it does not account for the area contributed due to a non-developable curvature (see text for discussion).

considerations. Those presented in Fig. 9(a & b) represent extreme cases for datum pin line location and the best datum pin line would probably lie somewhere in between. Two additional restorations are presented as alternatives (Fig. 9c & d). The first of these makes use of cross-section E as a datum pin line as it is centrally located within the area (Fig. 9c). The second (Fig. 9d) also uses cross-section E as a datum pin line up to the southernmost fault then assumes a component of sinistral slip during deformation (appears as dextral component on restoration) rather than dip-slip. As another extreme case of pin line positioning, a hinterland rather than foreland pin line has been used (Fig. 9e). This restoration is impossible as the loose points between cross-sections F and G cannot all be linked by restored bed line lengths. Therefore it cannot be considered a viable restoration for the interpretations presented on the set of cross-sections. If the structure was interpreted as a hinterland propagating sequence of structures then such a restoration may suggest that cross-section interpretations are incorrect. In practice, this result is common and an iterative process of re-interpreting cross-sections, checking that balance and other constraints are not violated, and restoration in three dimensions is required to arrive at a model which is restorable.

It may be possible to construct a series of balanced cross-sections that can be restored using any of the extreme pin line positions. This demonstrates that, as for balanced cross-sections, while a viable structural model can be constructed it may not necessarily be correct. However, if a restoration (as described above) can be constructed maintaining bed line lengths and approximately constant area then the structure depicted on cross-sections is, at least, compatible from section to section in three dimensions.

Before an appropriate restoration can be chosen the internal strain implied by the restoration must be considered. Because no penetrative structures are developed in the study area it may be expected that the internal strain is very small. This assumption is made during the restoration and can be tested by the implied deformation path which should not incorporate any significant internal strains. The least internally strained configuration for an unfolded grid block will be when all internal angles are close to 90° and the area of the block is therefore a maximum (Fig. 10). However, the restorations presented do not always allow for this condition to be maintained and, after unfolding, some blocks are restored to a distorted configuration (see Fig. 9). If the distortion is described by an angular shear parallel to the foreland edge of the block, then constructing a normal to this edge (i.e. a foreland edge normal) in its least internally strained state and comparing this to its restored, distorted shape allows a quantification of the distortions inherent in a particular restoration. The foreland edge normal (Fig. 10) can be pinned to the edges of a block because these remain the same lengths in both the least internally strained, but unfolded state and the distorted state. While most grid blocks show little or no apparent distortion, for some the distortion appears significant and the following test was carried out. The calculated tangents of angular shear for these blocks are shown (Fig. 9). If the internal strain (distortion) of these blocks is considered large enough to produce a cleavage when none is observed in the field then the restoration should be considered inadmissible. An ideal restoration, if internal strain is zero, would be one in which every grid block can be restored to its least internally strained configuration. The restoration shown in Fig. 9(d) minimises the distortion of the restored grid blocks inherent in the three previous restorations and is therefore considered the best restoration of those carried out. It implies that the bulk deformation includes a generally negligible distortional strain.

A three-dimensional restoration which uses bed line lengths between cross-sections and which, if only superficially, accounts for deformed state and restored state bedding surface areas, provides many more constraints than would be applicable to balanced cross-sections alone. The technique used here not only enhances viability (e.g. Elliot, 1983) but also has the potential to provide insight into the kinematic development of structures. Paradoxically, the restoration shows that the deformation is not plane strain and therefore constructing balanced cross-sections is strictly not valid. However, the material moving in and out of the plane of the cross-section is small compared to the amount of material moving along section lines during deformation. The use

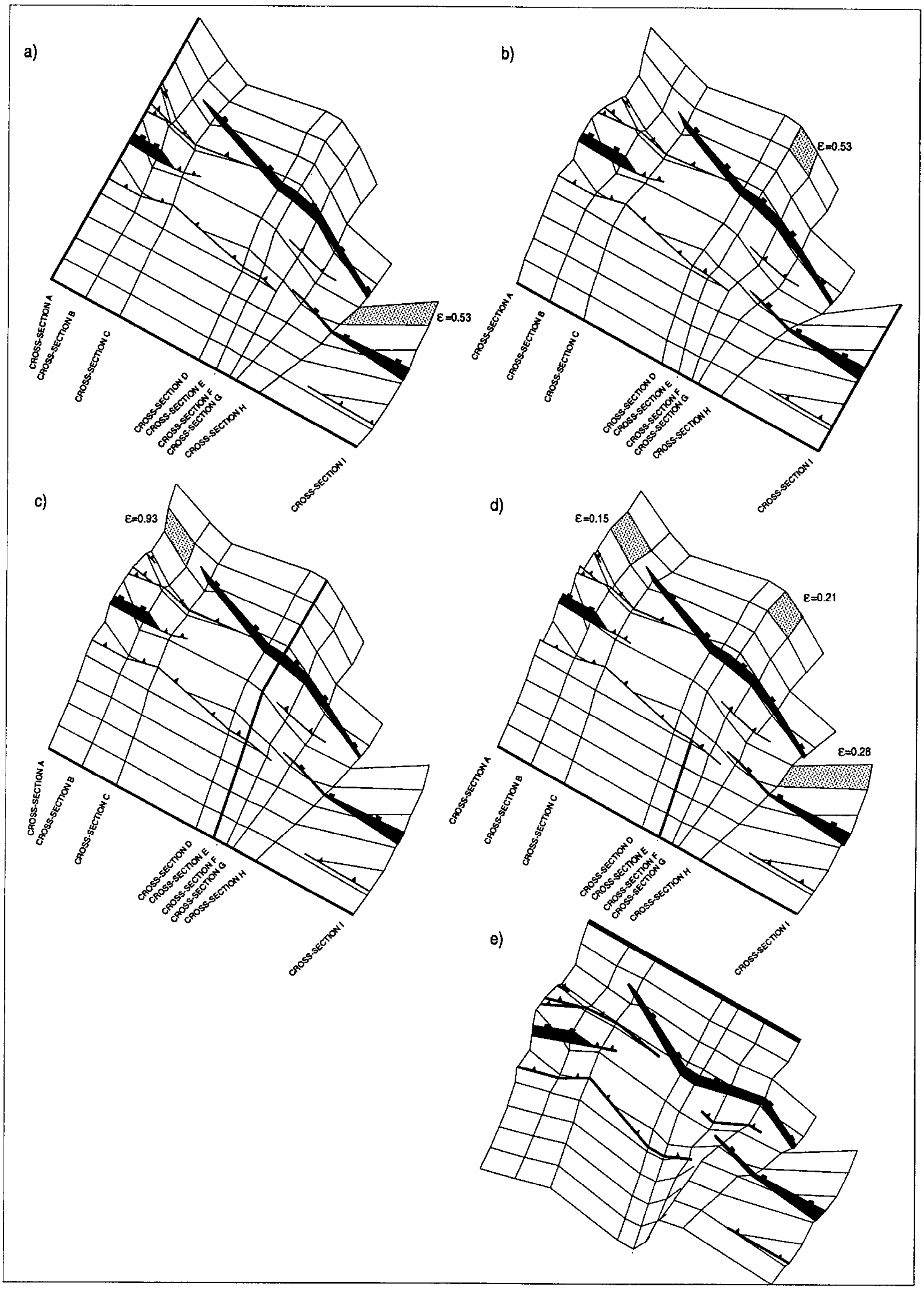

Fig. 9. Restoration of the top Toro sandstone using loose points to form a restored state grid. Cross-sections are marked as for previous figures. Dip-slip displacement is assumed for all faults and therefore all loose points are matched up across faults for restorations (a), (b) and (c). Restoration shown in (d) assumes a small component of sinistral slip on faults during deformation. Restorations (a), (b), (c) and (d) are pinned at the foreland-most loose point cross-section and the datum pin varies from (a) westernmost cross-section, (b) easternmost cross-section, (c) centrally located cross-section E, and (d) cross-section E south of the first fault with restoration to the north controlled by component of strike-slip motion. Pin lines are indicated by thicker lines. The angular shear for a distorted grid block (shaded) from each of restorations (a), (b) and (c) has been calculated and shown as a tangent (ie. $\gamma = \tan\alpha$, see Fig. 11). The angular shear for the same blocks have been calculated for restoration (d) where they are significantly reduced (see text for discussion). Restoration (e) uses a hinterland pin line which assumes a foreland to hinterland propagating sequence of structures. Grid blocks between cross-sections F and G cannot be linked. This restoration cannot therefore be considered viable.

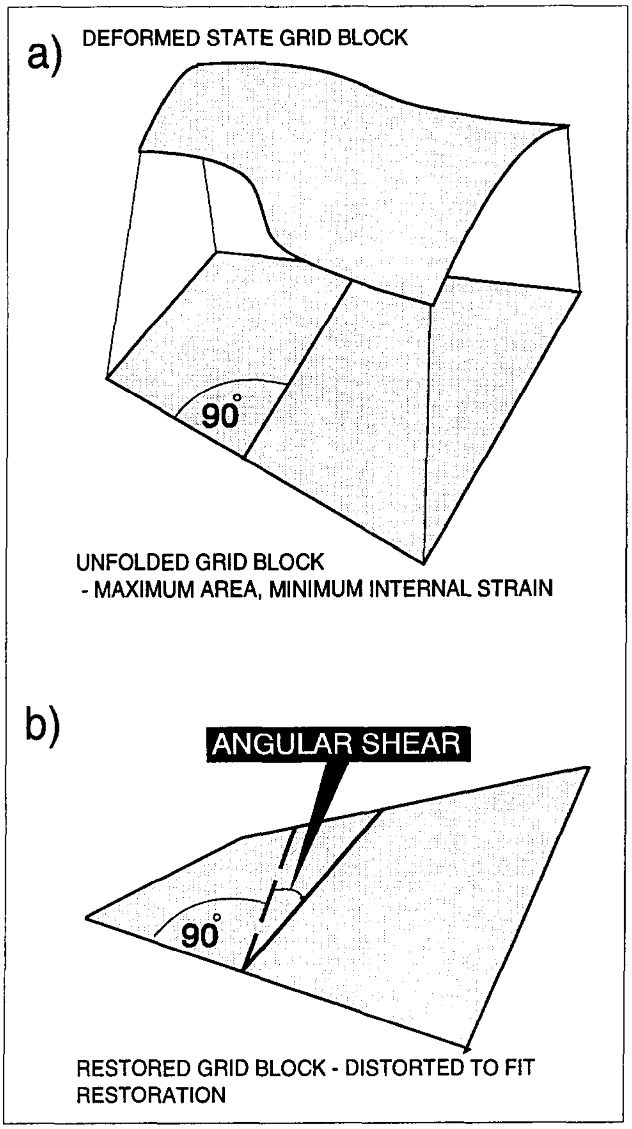

Fig. 10. (a) Folded grid blocks are first unfolded by straightening the edges of the block. (b) The grid block is then distorted as necessary to fit the restored configuration of surrounding blocks. If it is assumed that there is no internal strain in the restored layer then the optimum restoration is one which involves no distortion of the grid blocks. The distortion may be quantified by the angular shear (α) of a line intially perpendicular to the foreland edge of the grid block.

of balanced cross-sections which are restorable in three dimensions is thought to provide a more constrained structural model.

Kinematics

The translation component of the deformation may be specified by a displacement field whose fixed reference is the foreland pin line (Fig. 11). Since each grid block is assumed to be essentially internally unstrained, the rotations about vertical axes during deformation are specified by the rotation of block edges from the restored state to the deformed state. Rotations about vertical axes have been represented by form lines which show the amount of rotation compared to a fixed reference line (see Fig. 12). These form lines have been constructed by joining line segments representative of the rotation undergone by a grid block edge during deformation.

The displacement field is, as one might expect, characterised by displacements which decrease towards the foreland. Similarly, rotations of grid blocks also decrease in this direction. However, the set of compatible balanced cross-sections showing apparently reasonable variations in shortening also show rotations about vertical axes up to approximately 40°.

Rotations about vertical or steeply plunging axes are documented for fold belts world wide, for example, the Himalayas (Bossart *et al.*, 1989, 1990), the Appalachians (Kent, 1988) and the southern Pyrenees (Bates, 1989; Dinares *et al.*, 1992). Typically, and as in the examples cited above, rotations are quantified using palaeomagnetic data. Often rotations about vertical axes are unsuspected because they cannot be detected by conventional structural studies (Dinares *et al.*, 1992). The three-dimensional restoration method used here, in rocks which show no obvious internal deformation and for which it is assumed that differential shortening is not accommodated by shear strains, may be used in a similar fashion as palaeomagnetic data to constrain the kinematic evolution of structures developed in fold belts.

DISCUSSION AND CONCLUSIONS

Fold formation due to inversion

The model described has attributed the evolution of the Alice anticline to the inversion of pre-existing extensional faults. Differential shortening between sections is apparent and may be due to several underlying reasons, e.g. the sedimentary pinching out of a favourable glide horizon or décollement, or by the physical pinning of deformation. Both of these form obstacles to the path of a deformation front and will result in a curvilinear geometry for fold axes and thrust tip lines (Marshak *et al.*, 1992). Inversion of a pre-existing extensional fault is less reliant on a stratigraphically controlled décollement and therefore it is probable that differential shortening was due to physical pinning during development of the Alice anticline.

Rotation about vertical axes

Three-dimensional restoration has revealed a significant component of rotation about vertical axes implying that inversion has not been accomplished by plane strain deformation. Plotting rotation form lines with the restored map position of the extensional fault system (Fig. 13) shows that relay zones associated with the stepping of the normal fault broadly coincide with the regions of pinning. The inhibition of contractional

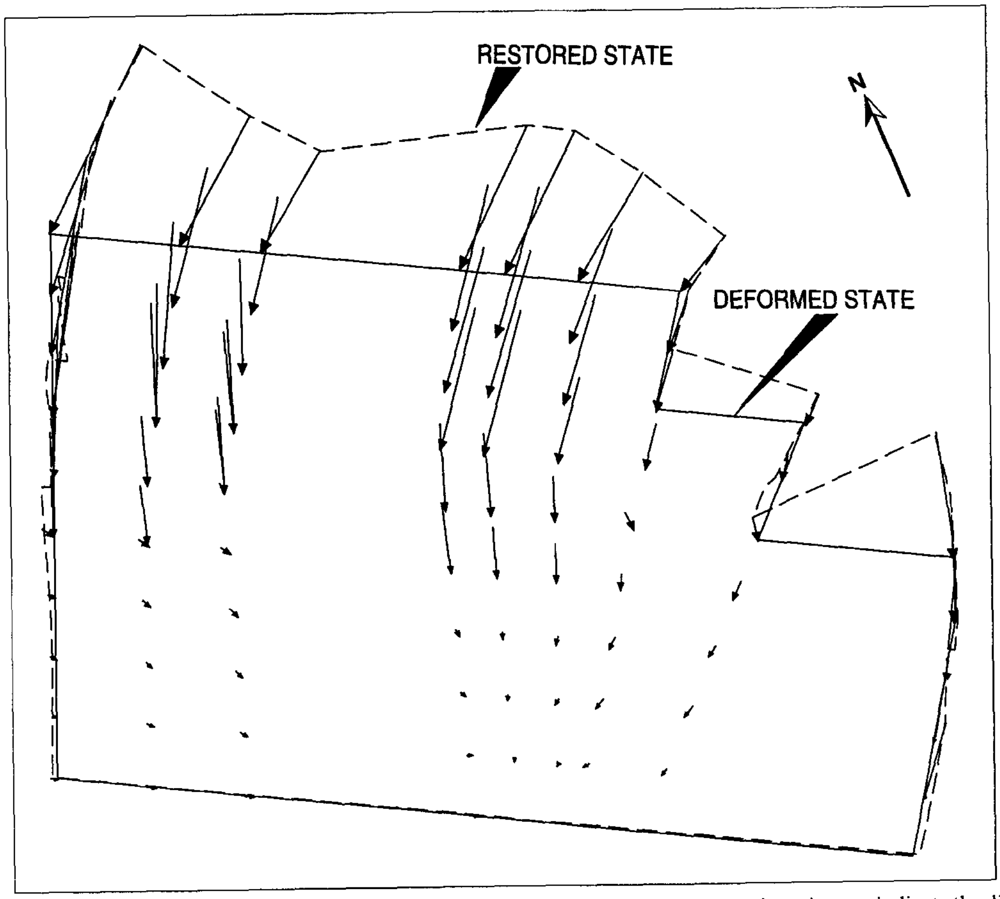

Fig. 11. Finite total displacement field obtained from initial and finite positions of loose points. Arrows indicate the direction of the displacement, and lengths of lines indicate values of displacement. The dashed perimeter line indicates the restored (initial) state and the solid line indicates the finite state.

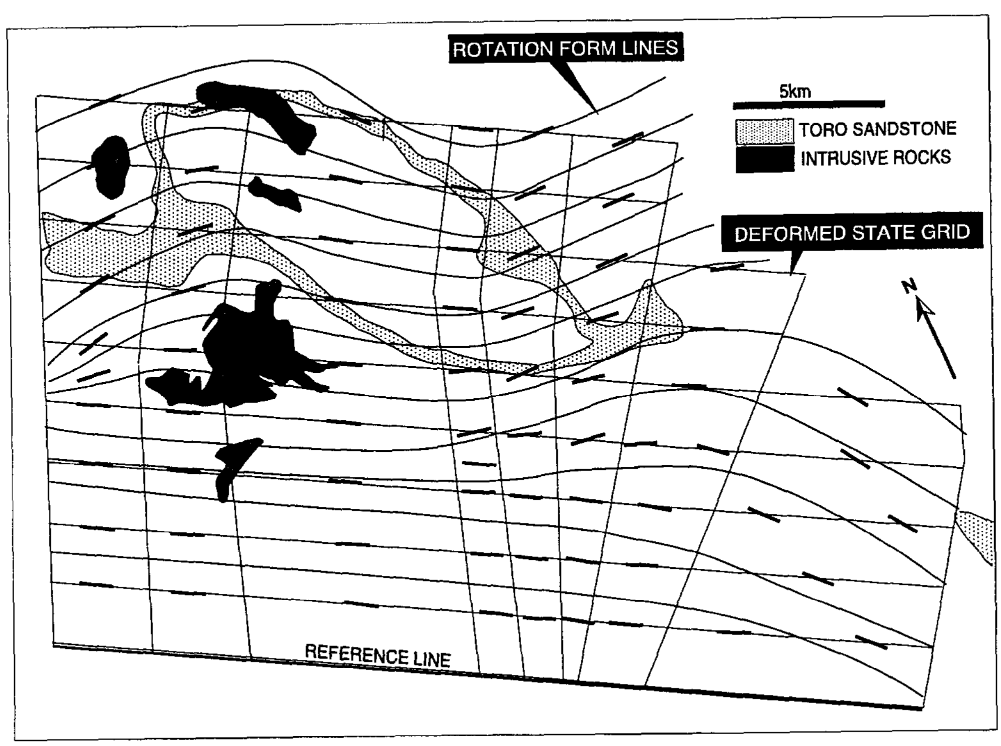

Fig. 12. Rotation form lines. These form lines represent the amount of rotation about a vertical axis undergone by grid block edges during progressive deformation, relative to a fixed reference line. Small, dark line segments represent the amount of rotation about a vertical axis undergone during deformation by the line segments of the deformed state grid on which they lie. These have been determined by comparison of the orientations of loose point lines in the deformed and restored states. The form lines smoothly represent these rotations.

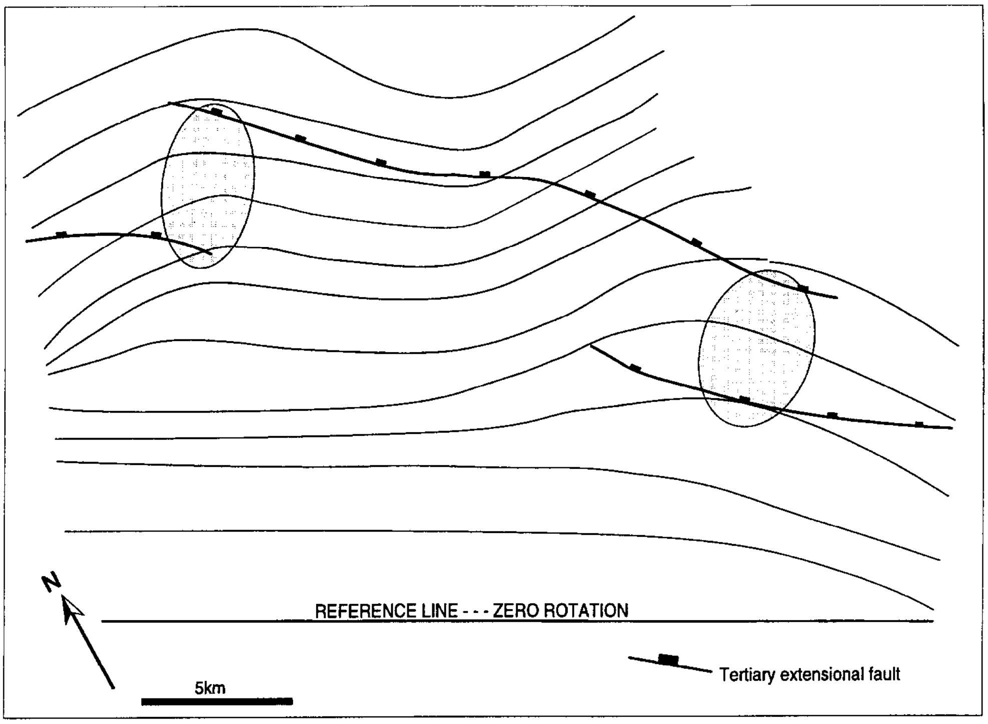

Fig. 13. Rotation form lines indicate two regions where progressive deformation has been pinned (indicated by shaded areas). These regions of pinning coincide with the original extensional fault system relays or 'off-steps' to which the pinning of deformation is therefore attributed.

deformation (pinning) may therefore be attributed to the relay zones developed between segments of the Tertiary extensional fault system. This suggests that the original extensional fault system geometry was characterised by soft linkage of the faults rather than by formation of discreet transfer zones which, upon contractional deformation, would tend to compartmentalise the deformation.

Restoring contractional deformation of the Kauwol anticline (Fig. 9d) indicates that during inversion contractional deformation exceeded the original extension, resulting in the lateral propagation of the fault as a thrust. This appears to be in response to inversion of the extensional fault well past its null point. Continuation of this process could lead to fault growth by segment linkage (Cartwright *et al.*, 1995) therefore removing obstructions to progressive deformation. Deformation dominated by bulk translation could then proceed with little rotation. However, rotations about vertical axes which may have occurred prior to fault segment linkage would remain.

The three-dimensional model including the restored (initial) and finite states may be used to accurately restore the positions and orientations of any point contained within. For example, the finite orientations of fractures in the Alice anticline area formed due to early imposed stresses can be related to the deformation paths, including rotations about vertical axes, specified by the three-dimensional restoration (Mason, 1994).

Kinematic implications

A commonly invoked process involves bedding 'rolling through' fold axial surfaces during fault-bend fold formation. For bedding to roll through an axial surface, a particular part of a bed must become strained and apparently 'unstrained' as it moves from a limb through a hinge and back to a limb position. In most examples there seems to be little evidence to demonstrate this process. If it is considered that folds in the Alice anticline area form and develop progressively during deformation and that fold axes have orientations largely fixed by the orientation of underlying extensional faults, then beds must have rolled through fold axial surfaces to have attained the rotations specified by the three-dimensional restoration (Fig. 14).

If structures form before encountering an obstruction, they will be curved by progressive deformation. However, if structures develop at the obstruction to deformation, they may assume an initial curvilinear trace (Marshak *et al.*, 1992). The Alice anticline formed by inversion of Tertiary extensional faults which contain inherent obstructions to contractional deformation in the form of relay zones. Contractional deformation has been pinned at these zones yet it is only subtly reflected in the curvature of thrusts and folds. This can be attributed to the fact that much of the rotational deformation has been accomplished by beds rolling through a structure which is fixed in space. It might be expected that for significant

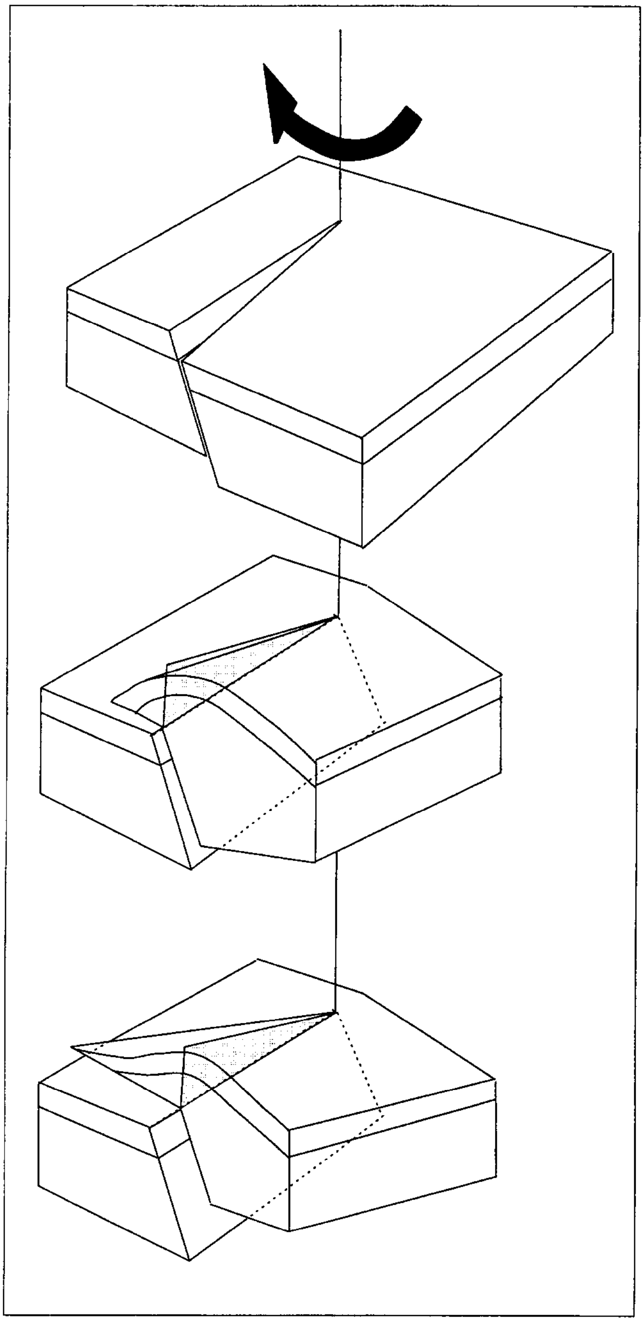

Fig. 14. Rotation of bedding about a vertical axis during deformation through a fold hinge which is fixed by the position of an underlying, originally extensional fault. Rotation is not reflected by fold axis orientation.

curvature of structures to develop, the structures must become 'locked up' (Price and Cosgrove, 1990) thus precluding the migration of beds through the structure. If bedding can migrate through structures which are fixed at the site of obstruction, then curved structures need not have formed with a primary curvature but may only become curved when the developing fold locks up. Thus records of rotation about vertical axes in the form of curved fold axes may not be preserved. In such cases, methods, such as that described here, or palaeomagnetic evidence will be required to detect rotations about vertical axes.

Acknowledgements—This study forms part of a Ph.D. thesis at Imperial College and I thank my supervisors Mike Coward and Bruce Hobbs who have both made helpful comments on this work. Critical comments by Paul Williams, Yanhua Zhang and Ken Baxter improved this paper. I am grateful to Ok Tedi Mining Limited for providing logistical and financial support for this study. The Australian Geodynamics Cooperative Research Centre is acknowledged for support provided during the preparation of this manuscript. Reviews by J. Willis and K. Neilsen considerably improved the manuscript.

REFERENCES

Arnold, G. O., Griffin, T. J. and Hodge, C. C. (1979) Geology of the Ok Tedi and southern Atbalmin 1:100,000 sheet. *Geological Survey Papua New Guinea Report* 79/3.

Bates, M. P. (1989) Palaeomagnetic evidence for rotations and deformation in the Nogueras Zone, Central Southern Pyrenees, Spain. *Journal of the Geological Society, London* **146**, 459–476.

Bitterli, T. (1990) The kinematic evolution of a classical Jura fold: a reinterpretation based on 3-dimensional balancing techniques (Weissenstein Anticline, Jura Mountains, Switzerland). *Eclogae Geologicae Helvetiae* **83**, 493–511.

Bossart, P., Ottiger, R. and Heller, F. (1989) Palaeomagnetism in the Hazara–Kashmir syntaxis, N.E. Pakistan. *Eclogae Geologicae Helvetiae* **82**, 585–601.

Bossart, P., Ottiger, R. and Heller, F. (1990) Rock magnetic properties and structural development in the core of the Hazara–Kashmir Syntaxis, N.E. Pakistan. *Tectonics* **9**, 103–121.

Boyer, S. E. and Elliott, D. (1982) Thrust systems. *Bulletin of the American Association of Petroleum Geologists* **66**, 1196–1230.

Burns, B. J. and Bein, J. (1980) Regional geology and hydrocarbon potential of the Mesozoic of the western Papuan Basin. *APEA Journal* **20**, 1–15.

Cartwright, J. A., Trudgill, B. D. and Mansfield, C. S. (1995) Fault growth by segment linkage: an explanation for scatter in maximum displacement and trace length data from the Canyonlands Grabens of SE Utah. *Journal of Structural Geology* **17**, 1319–1326.

Coward, M. P. (1994) Inversion Tectonics. In *Continental Deformation*, ed. P. L. Hancock, pp. 289–304. Pergamon Press, Oxford.

Coward, M. P., Gillcrist, R. and Trudgill, B. (1991) Extensional structures and their tectonic inversion in the Western Alps. In *The Geometry of Normal Faults*, eds A. M. Roberts, G. Yeilding and B. Freeman, pp. 93–112. Special Publication of the Geological Society, London **56**, 93–112.

Cooper, P. and Taylor, B. (1987) Seismotectonics of New Guinea: a model for arc reversal following arc–continent collision. *Tectonics* **6**, 53–67.

Davies, H. L. (1990) Structure and evolution of the border region of New Guinea. *Proceedings of the first Papua New Guinea Petroleum Convention*, eds C. J. Carman and Z. Carman, pp. 245–269.

Davies, H. L. and Norvick, M. (1974) Blucher Range 1:250 000 Geological Series. Australian Bureau of Mineral Resources Map and Explanatory Notes SB/54-7.

Dahlstrom, C. D. A. (1969) Balanced sections. *Canadian Journal of Earth Science* **6**, 743–757.

De Paor, D. G. (1988) Balanced sections in thrust belts Part 1: Construction. *Bulletin of the American Association of Petroleum Geologists* **75**, 73–90.

De Paor, D. G. (1988) Balanced sections in thrust belts Part 2: Computerised line and area balancing. *Geobyte* **May**, 33–37.

Dinares, J., McClelland, E. and Santanach, P. (1992) Contrasting rotations within thrust sheets and kinematics of thrust tectonics as derived from palaeomagnetic data: an example from the Southern Pyrenees. In *Thrust Tectonics*, ed. K. R. McClay. Chapman and Hall, London.

Dow, D. B. (1977) A geological synthesis of Papua New Guinea. *Australian Bureau of Mineral Resources Bulletin* **201**

Elliott, D. (1983) the construction of balanced cross-sections. *Journal of Structural Geology* **5**, 101.

Enfield, M. A. and Coward, M. P. (1987) The structure of the West Orkney Basin, northern Scotland. *Journal of the Geological Society, London* **144**, 871–884.

Geiser, P. A. (1988) The role of kinematics in the construction and analysis of geological cross-sections in deformed terranes. *Special Paper of the Geological Society, America* **222**, 47–76.

Gibbs, A. D. (1983) Balanced cross-section construction from seismic sections in areas of extensional tectonics. *Journal of Structural Geology* **5**, 153–160.

Haig, D. W., Perembo, R. C. B. and Lynch, D. (1990) Micropalaeontological analysis of samples from the Ok Tedi Region, Papua New Guinea. Report to Ok Tedi Mining Limited.

Hill, K. C. (1989) The Muller anticline, Papua New Guinea; basement-cored, inverted extensional fault structures with opposite vergence. *Tectonophysics* **158**, 227–245.

Hill, K. C. (1991) Structure of the Papuan Fold Belt, Papua New Guinea. *Bulletin of the American Association of Petroleum Geologists* **75**, 857–872.

Hill, K. C. and Gleadow, A. J. W. (1989) Uplift and thermal history of the Papuan Fold Belt, Papua New Guinea: apatite fission track analysis. *Journal of Australian Earth Science* **36**, 515–539.

Hobson, D. M. (1986) A thin skinned model for the Papuan thrust belt and some implications for hydrocarbon exploration. *APEA Journal* **26**, 214–224.

Home, P. C., Dalton, D. G. and Brannan, J. (1990) Geological evolution of the western Papuan Basin. *Proceedings of the First Papua New Guinea Petroleum Convention*, eds C. J. Carman and Z. Carman, pp.107–117.

Hossack, J. R. (1979) The use of balanced cross-sections in the calculation of orogenic contraction: a review. *Journal of the Geological Society, London* **136**, 705–711.

Jaques, A. L. and Robinson, G. P. (1977) Continent–island-arc collision in northern Papua New Guinea. *Australian Bureau of Mineral Resources Bulletin* **2**, 289–303.

Jenkins, D. A. L. (1974) Detachment Tectonics in Western Papua New Guinea. *Bulletin of the Geological Society, America* **85**, 533–548.

Kent, D. V. (1988) Further palaeomagnetic evidence for oroclinal rotation in the central folded Appalachians from the Bloomsberg and Mauch Chunk formations. *Tectonics* **7**, 749–759.

Lamerson, P. R. (1990) Evolution of structural interpretations in the Iagifu/Hedinia field, Papua New Guinea. *Proceedings of the First Papua New Guinea Petroleum Convention*, eds C. J. Carman and Z. Carman, pp. 283–300.

Laubscher, H. (1987) The kinematic puzzle of the Neogene Northern Andes. In *The Anatomy of Mountain Ranges*, eds J.-P. Schaer and J. Rodgers, pp. 211–227. Princeton University Press, Princeton.

Lisle, R. J. (1992) Constant bed-length folding: three-dimensional geometrical implications. *Journal of Structural Geology* **14**, 245–252.

Marshak, S., Wilkerson, M. S. and Hsui, A. T. (1992) Generation of curved fold-thrust belts: Insight from simple physical and analytical models. In *Thrust Tectonics*, ed. K. R. McClay. Chapman and Hall, London.

Mason, R. A. (1994) Structural evolution of the western Papuan Fold Belt, Papua New Guinea. Unpublished Ph.D. thesis, University of London.

Mitra, S. and Namson, J. (1989) Equal area balancing. *American Journal of Science* **289**, 563–599.

Pigram, C. J. and Davies, H. L. (1987) Terranes and the accretion history of the New Guinea orogen. *Australian Bureau of Mineral Resources Journal of Australian Geology and Geophysics* **10**, 193–211.

Price, N. J. and Cosgrove, J. W. (1990) *Analysis of Geological Structures*. Cambridge University Press, Cambridge.

Reches, Z. (1976) Analysis of joints in two monoclines in Israel. *Bulletin of the Geological Society, America* **87**, 1654–1662.

Smith, R. I. (1990) Tertiary plate tectonic setting and evolution of Papua New Guinea. *Proceedings of the First Papua New Guinea Petroleum Convention*, ed. C. J. Carman and Z. Carman, pp. 229–244.

Texaco (1972) Elevala seismic survey, permit to explore p.27, Papua. Compagnie Generale de Geophysique for Texaco Overseas Petroleum Co.

Williams, G. D., Powell, C. M. and Cooper, M. A. (1989) Geometry and kinematics of inversion tectonics. In *Inversion Tectonics*, eds M. A. Cooper and G. D. Williams, pp. 3–15. Special Publication of the Geological Society, London **44**,.

Woodward, N. B., Boyer, S. E. and Suppe, J. (1985) *An Outline of Balanced Cross-sections*. University of Tennesee, Studies in Geology **11**.