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Balanced cross-section construction from seismic sections in areas of extensional tectonics

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Abstract—The application of the technique of balanced section construction, initially developed for areas of compressional folding and faulting, is reviewed with reference to extensional tectonics. A number of examples are discussed where these techniques have been successfully applied in the North Sea. The interpretation of geoseismic sections is considered to be greatly assisted by careful application of geometrical balance and a consideration of strain even in areas of low crustal extensions. The nature of seismic sections, however, places limitations on the validity of balancing which must be borne in mind with such interpretations and wherever possible the balancing of a geoseismic section should be confirmed by complete depth conversion. The rapid testing of the integrity of the geoseismic section by attempting to balance the section at the interpretational phase can eliminate many problems as well as allowing the fullest use to be made of the geophysical information.

INTRODUCTION

THE CONSTRUCTION of accurate geological cross-sections is of the greatest importance to all branches of geology but is of paramount importance when large commercial investments are at stake. For this reason balanced section techniques have evoked considerable interest, in particular in areas of overthrusting (Elliott 1977). In extensional regimes, however, much less work has been done, partly because finite extensions are commonly fairly small and the tectonic style may be deceptively simple. This paper considers some of the problems of applying balanced section techniques to areas of extensional tectonics with reference to problems encountered in the North Sea.

While virtually all the geometrical constructions used in balanced sections have been worked out for regions of contractional tectonics particularly since the synthesis of Dahlstrom (1969a,b, 1970) there are a number of problems which are special to extensional regimes, where major errors can be made. In addition, the primary data is likely to consist entirely of seismic reflection lines with or without well control. In contrast, in many of the areas of contractional tectonics, where section balancing techniques have been successfully applied, field mapping can be used and supplemented by seismic and well data. Field observation allows accurate estimates of ductile strain to be made, and for this to be accounted for in the construction of any palinspastic sections. Removal of ductile strains (e.g. Hossack 1979, Schwerdtner 1977, Borradaile 1979, Elliott & Johnson 1980) in addition to rotational and translational strains may be possible. Strain heterogeneity may also be estimated and its possible effects on balance calculations deduced. This is rarely possible in areas of extensional tectonics such as in the North Sea. The availability of closely spaced seismic lines, coupled with well control, however, can give three-dimensional and stratigraphic control rarely possible in areas of orogenic contraction.

THE BALANCED SECTION

The basic approaches to section balance assume plane strain, or conservation of cross-sectional area. Chamberlin's (1910, 1919) calculation of equal areas for a section deformed above a décollement or detachment surface can be applied to extension as well as contraction. Figure 1 shows this where the area A before deformation equals the area B after deformation. The area C is common and hence the equation which expresses the relationship between the undeformed length, the deformed length of

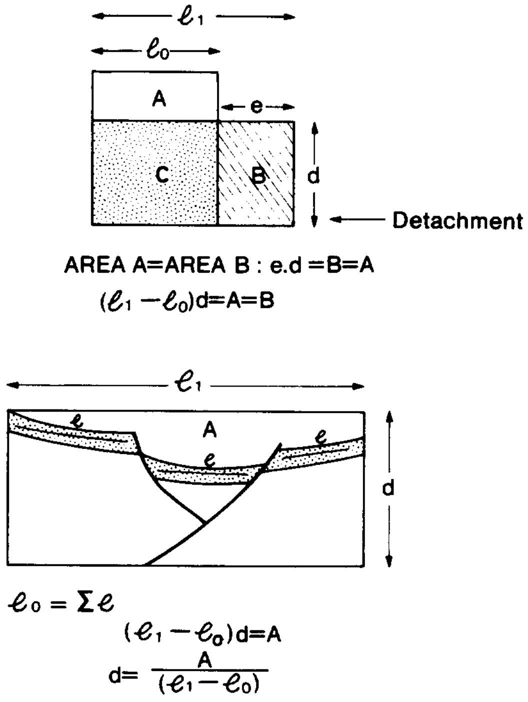

Fig. 1. Area balance for extension. Above: l_0 is original length of section which is compared with length in deformed state and area. Below: the regional projected horizontal, to calculate depth to detachment. See text for details.

section and the depth to the décollement surface, d, is given by: $l_0 = l_1 + A/d$ (Elliott 1977; after Gwinn 1970) where A is the cross-sectional area. This can be expressed in terms of average stratigraphic thickness, d, above the décollement surface: $l_0 = l_1 d_1/d_0$, or in terms of the extension, e, measured as conventional engineering strain ($e = (l_1 - l_0)/l_0$) where the equation is written as $d_1 = A/e$. The extension factor, β (McKenzie 1978a,b), may be substituted for unit length $l_0 : \beta = (1 + e); \beta = l_1/l_0$.

These equations are seen to be identical to those for orogenic contraction (Hossack 1979) with the exception of the change in sign convention for e and are likewise independent of the style of deformation. The geometry represented on any cross-section should satisfy these equations and depending on the data available balanced lengths and/or areas are used as appropriate.

The sections may not appear to satisfy these conditions for a variety of reasons. Firstly, the section may not be normal to the tectonic strike, that is, it may not be parallel to the extension direction. In this case the data can be projected on to such a section or allowance can be made for the angular deviation of the section and the extension direction.

$$l_\lambda = (l_c^2 - (S.\sin\alpha)^2)^{1/2},$$

where l_λ is length in the section normal to tectonic strike, and is observed in a section at α to this dip section and l_c is length of observed segment over horizontal distance S. The dip of l_λ, θ_λ is given by

$$\theta_\lambda = \sin^{-1}(S.\sin\alpha/l_\lambda).$$

Secondly, there may be extension along the tectonic strike when the relationship: $(l + e_1)(l + e_2)(l + e_3) = l + \Delta$, where Δ is the volume strain, $\delta V/V$ will be satisfied. To allow for this case Hossack (1978) used the method of integrating the measured finite strains along the intermediate finite strain trajectories to calculate the average strike elongation assuming constant volume. Hossack's approach holds equally for extensional deformations.

The assumption of plane strain in balanced cross-sections has been criticized (e.g. Geiser 1978). The large volume changes which can accompany diagenesis (Sanderson 1976) and tectonic deformation (Wood 1974, Ramsay & Wood 1973) can lead to volume changes possibly in excess of 40%. Mass transfer by pressure solution may also be present and again large volume changes may occur (Plessman 1964, Durney & Ramsay 1973, Elliott 1973).

COMPACTION

Both compaction changes and pressure solution changes in volumes of this order of magnitude are recorded from the North Sea area. For contractional tectonics, Hossack (1979) discussed how these volume changes may be discounted, or have net effects which are small in relation to other strains. For example, compaction usually occurs before deformation and, therefore, the tectonically undeformed compacted state is compared with the deformed state and the compaction is the same in each case. It may also be a valid assumption for pressure solution that the volume loss has uniaxial symmetry or that the material is redeposited locally.

In areas of extensional tectonics such as the North Sea many of these assumptions do not apply. Compaction is probably the most important element of the finite strain with the exception of brittle faulting. As the compaction may be both synchronous with, and post-date the tectonic deformation it is essential to account for this in any balance calculation, and subsequent palinspastic reconstruction. Estimates of compaction can, in some cases, be made from direct measurement of deformed objects such as reduction spots and burrows recovered during coring using a variety of techniques such as those outlined by Ramsay (1967). Unfortunately such measurements only apply to discrete intervals and often to only one lithology. Nevertheless they do allow a realistic estimate of average compaction strain to be used. An alternative approach is to use compaction curves for depth of burial (Steckler & Watts 1978, Sclater & Christie 1980) and to expand the section progressively during back stripping (see Wood 1981). However, with rapid burial or erosion the present depth may not reflect the actual compaction and a more direct method is to estimate compaction from the sonic log (Magara 1976a,b, 1978). In the case of the example illustrated in Fig. 2 compaction estimates using the direct measurement of reduction spots in cores and Magara's technique in a number of wells on the structure both gave comparable values of about 30% for volumetric strain. The application of this volume compaction to the section improves the reconstruction in the vicinity of areas of complex faulting (cf. Figs. 2b & c) and allows the very low observed dips and 'horse tailing' of the main fault (MF) in the shale sections overlying the reservoir to be attributed to progressive compaction (Fig. 2). 'Horse tailing' of normal faults is frequently seen on seismic interpretations and is analogous to splaying in strike-slip faulting. The analysis discussed here suggests a progressive 'younging' of the splay faults away from the footwall during syntectonic compaction. In addition it is necessary to postulate movement on the secondary fault (SF) to down-fault the crest of the horst after the formation of the main horst edge by movement on the main fault. Bedding-plane slip or flow in the overlying shale section must also be accommodated at this time. In this case the constraints of balancing the section provide an insight into a common and fundamental process of horst and graben formation with the active deformation moving outwards from the graben axis with time. The progressive retreat of horst lip away from the graben axis results in dip changes of the earlier-formed faults and may lead to faults generated as normal faults being rotated into a reverse geometry (Fig. 3) (see Profett 1977, Wernicke & Burchfiel 1982).

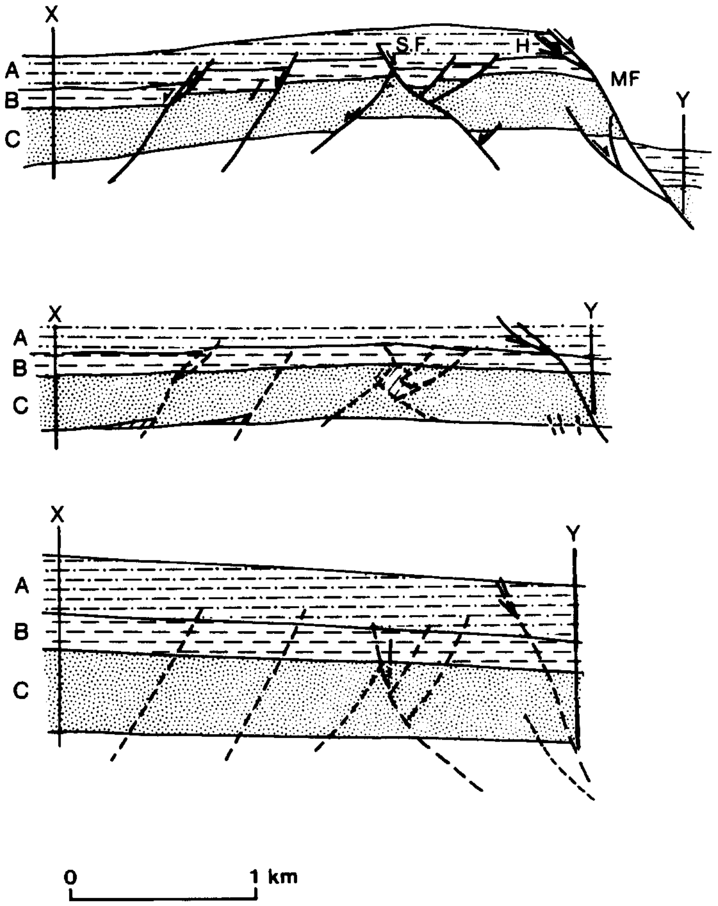

Fig. 2. Sections across a horst block showing respectively: (top) geological section compiled from seismic data; (middle) first attempt at reconstruction by 'jigsaw' technique, note area deficit shown by an oblique lined ornament; and (bottom) final reconstruction after decompaction and allowance for differential compaction.

LISTRIC FAULTS AND ROTATION

A further problem which is not normally encountered in contractional tectonics is that of growth faulting and syntectonic erosion and deposition. Growth faulting (Rider 1978, Crans *et al.* 1980, Crans & Mandl 1980) on a low-angle listric gravity slide may usually be distinguished on geoseismic sections from syn-sedimentary fault activity on deep-seated structures by the presence of roll-over and by use of a depth to detachment calculation. A case of shallow detachment which is controlled by basement faults is illustrated in Fig. 4 (after Heybroek 1975). Detachment is on Zechstein evaporites and comprises listric faulting and halokinesis towards the deeper parts of the basin. Such thin-skinned extensional tectonics may be much more prevalent than is realized even outside areas of Zechstein salt movement and can be recognized as both local and regional events. The distinction, however, on seismic sections between growth faults *sensu stricto* and synsedimentary sliding (growth faults *sensu lato*), which both obey the same geometric rules, is important in determining the effect on sedimentation. It may be advantageous to establish the timing of the syn-sedimentary fault activity by plotting a growth curve (Fig. 5) and discontinuities in the curve can be used to identify periods of erosion and reactivation on the fault.

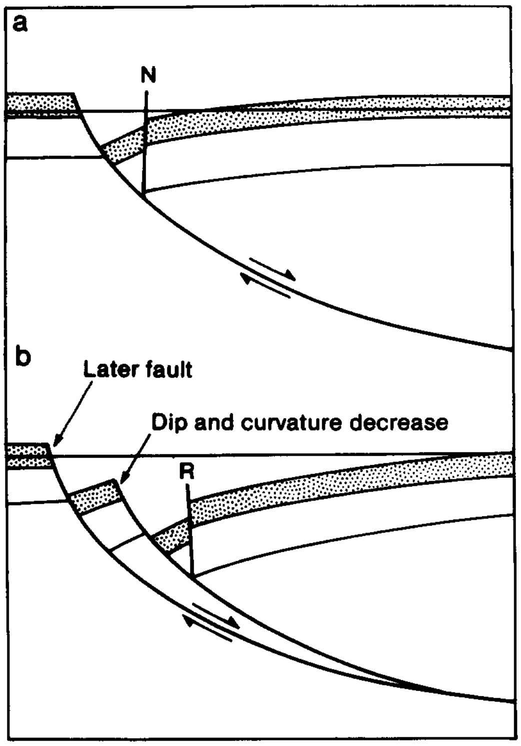

Fig. 3. Progressive migration and 'piggy-back' movement of listric normal fault resulting in (a) rotation of an early normal fault (N) on a roll-over and (b) an apparent reverse geometry (R) and flattening of the earlier synthetic fault.

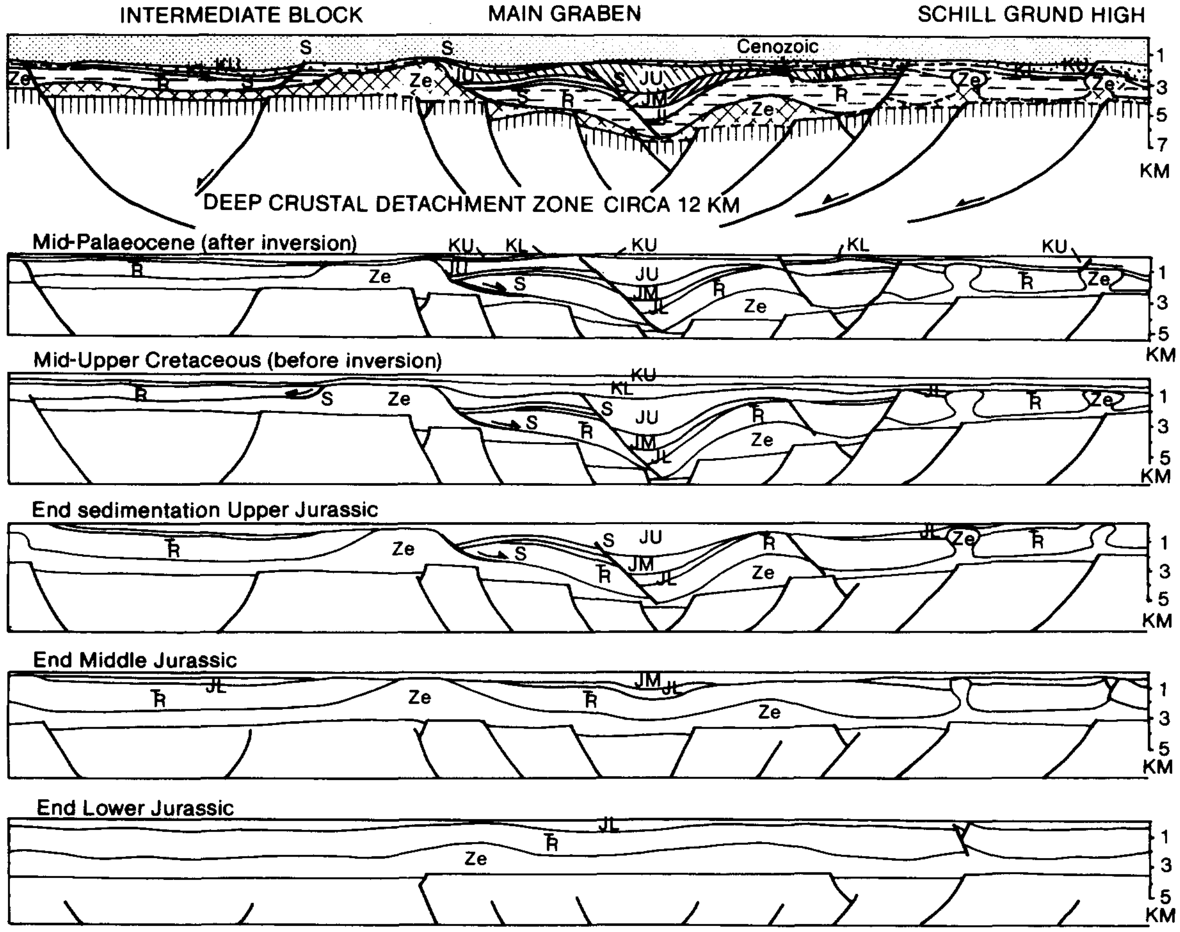

Fig. 4. Regional section balanced and reconstructed (after Heybroek 1975) by progressive back stripping of the sediments, removal of halokinetic effects and balancing the basement faulting. Note the decoupling zone in the Zechstein (Ze) combining low-angle listric normal faults (S) and halokineses towards the deeper parts of the basin. Also note the control of the higher level faulting by the deeper basement structures with drape and secondary faulting above the Zechstein.

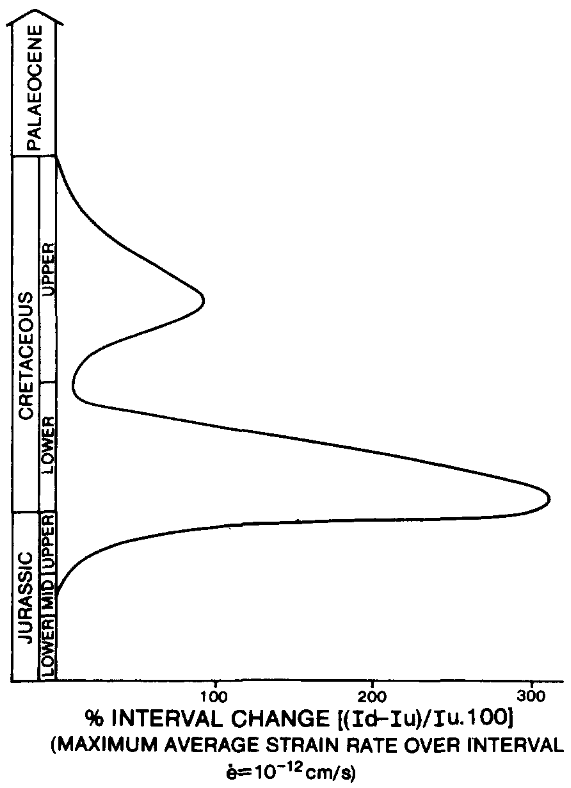

Fig. 5. Growth curve plotted for a fault from the Central graben showing two periods of fault activity and rapid growth. The average slip rate for the main phase is approximately 10^{-12} cm s^{-1}.

In order to calculate the true rate of faulting it is necessary to correct these curves for compaction on the foot and hanging-wall and then average tectonic strain rates ($\dot{e}$) may be calculated.

Well control may be necessary to confirm that the sequence on the upthrown footwall is condensed rather than eroded, and this is necessary before the section can be reconstructed. Partial reconstructions may be required for each formation and it may be impossible to balance the section in a single stage. Care should be taken that thickened sequences on the downthrown side of faults can be accounted for by the geological model if it exceeds that estimated from erosion of upthrown blocks within the immediate vicinity.

Dip changes seen across faults on geoseismic lines demonstrate that most faults are listric (Price 1977). Roll-over geometries can be used to construct the change of curvature of the listric fault (Fig. 6) and rely upon the necessity to avoid creating 'gaps' in the section during deformation. Errors in the use of this technique arise from differential compaction, but these should be small. An alternative approach is to use the rotation ϕ (in radians) given by the dip change across the fault and chord length, c, defined by the fault cut to calculate the rotation pole and radius of curvature, r:

$$r = \phi . c/2\pi.$$

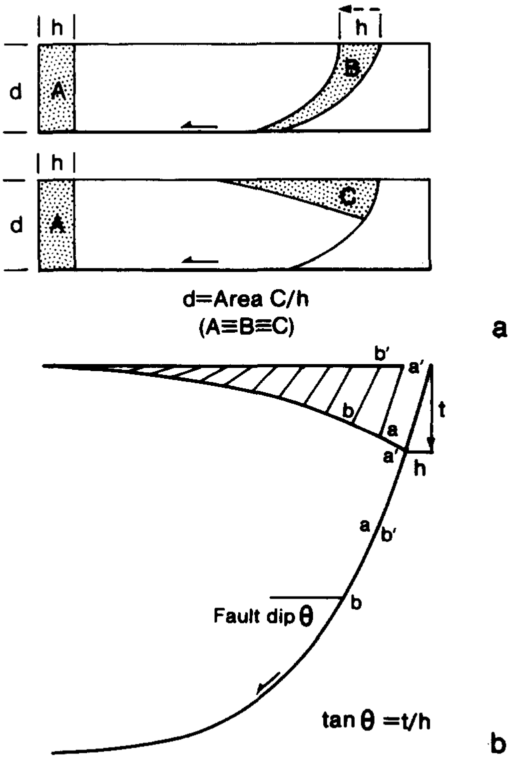

Fig. 6. (a) Roll-over geometry showing accommodation of area B for fault with heave, h. Areas A, B, and C are equal. (b) Fault plane constructed from shape of roll-over. Dip of fault plane segments a–a', b–b', etc. are given by tan θ = t/h and then projected to link up as fault plane.

In general, however, graphical methods are preferable as they will accurately generate faults with discontinuous rates of curvature. On seismic sections, however, antithetic and synthetic accommodation faults may be missed which can have a large effect on the constructed shape of the main listric fault. The requirement to maintain cross-sectional continuity has the important effect of predicting that a variety of syn- and antithetic accommodation faults are necessary in the absence of 'ductile' roll over. Figure 7 shows a variety of these geometries which can accompany deep-seated listric faults bounding major horst blocks. Crestal terraces, grabens and platforms of the sort predicted geometrically are common features of many North Sea Oil Fields (e.g. Blair 1975, Hallett 1980). The possibility that a small number of faults in these secondary structures could be reverse while the main deformation is extensional is of particular interest. As yet no undoubted structures of this type have been proved in the North Sea although a small number of cases where this is a possible model have arisen, where the well trajectory and fault dip do not allow a distinction to be made between a very steep normal fault and a reverse structure (Fig. 8). Reverse faults may be present both as direct result of this genetic process (Fig. 7) and as a result of later rotation (Fig. 3).

OBLIQUE SECTIONS

In areas such as the North Sea, the main source of structural data is derived from reflection seismic lines which are interpreted with reference to available well control. For this reason, even in well-known areas, the exact stratigraphic significance of a seismic event may not be known. Detailed stratigraphic knowledge may be confined to a narrow band in the section which corresponds to the reservoir horizon. A further problem is that while every effort is normally made in designing the seismic survey to shoot the lines parallel to the structural dip, that is in the profile, or principal plane of the extension this may not always be possible, nor desirable. Where more than one structural element is present, or the geology is poorly known the seismic lines may lie oblique to the plane of extension.

Where the seismic line is oblique it may be possible and desirable to project whatever data is present on to the profile plane before attempting to balance the section. This, however, implies the use of a model, or knowledge of the deformation style and introduces yet another level of interpretation into the data. It may also

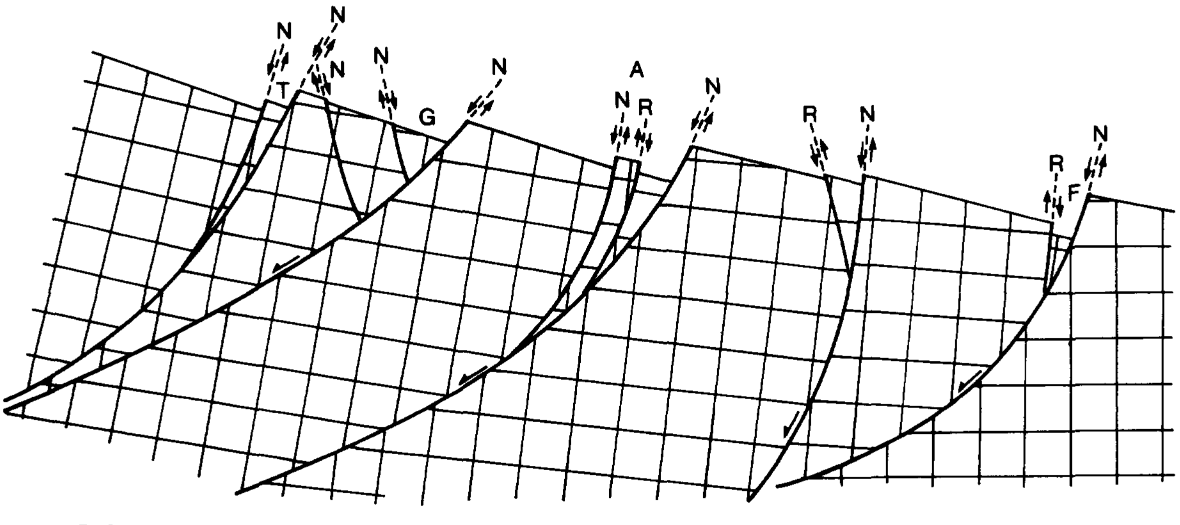

Fig. 7. Cartoon showing progressive rotation across listric normal faults and secondary structures produced by different combinations of syn- and antithetic accommodation faults. Note the crestal terrace (T), graben (G) horst (A) and horst-foot graben (F) as well as the possibility of a number of reverse faults (R).

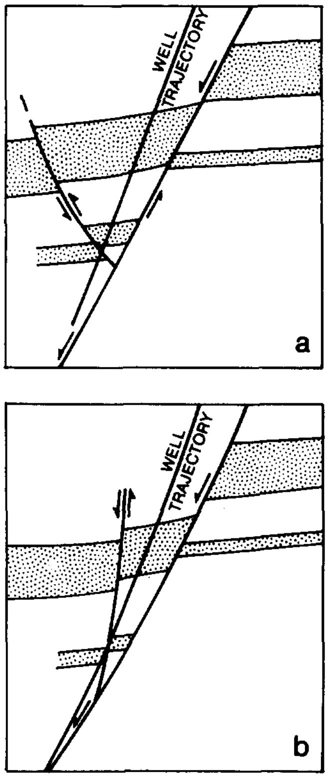

Fig. 8. Cartoon showing interpretation problems where data from an inclined well indicate a repeated section. (a) Interpretation with reverse fault and (b) with normal fault.

be, and frequently is, the case that the existing seismic line has been acquired to utilize well control and to help elucidate the structure between the wells. For these reasons it is often desirable to attempt to balance the oblique section rather than to extrapolate on to another section which may be of less value.

Balancing oblique sections is inherently difficult as area may not be maintained in the section. Two approaches are presently used to resolve this problem. The simplest technique is where the deformation has an 'orthorhombic' symmetry and the plane of section contains one of the deformation symmetry axes. This is frequently a valid assumption for crustal-parallel deformations of the type and scale of those investigated in the North Sea. Bed length measurements can be recalculated using the simple trigonometric relationship discussed above. Such a technique for oblique sections is described by Cooper (1983). Corrections for two way time (T) and velocity (v_i) over each interval must be made and a simplified form of the expression for l_λ becomes:

$$l_\lambda = (l_0 \sin\theta_0 + \left(\frac{T.v_i}{2}\right)^2 - (l_0 \sin\alpha \sin\theta_0)^2)^{1/2},$$

where θ_0 is observed dip and segment length $S = l_0 \sin\theta_0$. Bed lengths are then summed over the appropriate segments and used in bed length and depth to detachment calculations. In many cases a rough check of lengths and areas using this sort of simplified equation to take velocity effects into account is sufficient to give a feel for the errors introduced in balancing time rather than depth sections. Where the section does not contain one of the deformation axes, or the deformation lacks orthorhombic symmetry a number of successive trigonometric operations can be made as outlined by Cooper (1983). As the strain tensor is non-commutative this approach is theoretically unsound and can lead to substantial errors. More sophisticated geometric manipulations may be attempted, but in general involve assumptions which cannot be justified in terms of known errors and uncertainty in the data.

The problem of adequately defining the strain tensor can be avoided largely by an empirical approach where a number of non-parallel seismic lines are available. Provided that the line spacing is less than the spacing of the structures an integrated area balance can be made. Accurately depth-converted sections are again desirable but over a small seismic interval may not be necessary in terms of other inherent errors. The technique hinges on the assumption that volume is conserved during deformation, and while volume may be apparently lost in one section it should be gained in another adjacent section. Careful planimetering or otherwise estimating volume on successive lines enables an areal volume balance to be established. This approach has the added advantage of giving valuable clues to the geometry of the finite strain ellipsoid. It should be possible to establish, for example, the plane of no finite longitudinal strain. Where parallel seismic lines cross an area of suspected strike-slip faults, comparison of areal balance on successive lines can assist in establishing displacement on the wrench fault system. This approach has been used to test the hypothesis of post-Jurassic strike-slip faulting in part of the Inner Moray Firth, and along with other data showed that such a model was not necessary to account for observed fault displacements and sediment distributions. Mapped fault patterns with apparent Riedel shear geometry could, in this case, be attributed to the later normal faults inheriting an earlier basement trend.

GEOSEISMIC SECTIONS

Seismic reflection data rarely allow fault geometries to be observed directly and geoseismic sections inevitably consist of interpretation and models of differing confidence. For example, the throw of the fault on the section plane may be known with some certainty and after drilling of an adjacent well the seismic prognoses may be confirmed. The dip of the fault plane and possible existence of antithetic accommodation faults on the other hand may not be supported by any information other than the structural model. The only reliable interpretation tool in such cases is that of geometrical balance.

As many of the North Sea reservoirs are highly faulted with, in some cases, pressure sealed fault compartments, the ability to test the geometrical integrity of a fault pattern mapped in section and plan is of paramount importance. Even if it remains impossible to achieve a uniquely satisfactory balance, the knowledge gained by interpretative attempts to balance the model can be important. For example, secondary horsts and crestal grabens on the larger structure may consist of numerous small faults with displacements less than the resolution of the seismic technique. The ability to define the extent of such areas where an unresolved space problem exists may assist in siting wells.

Balanced sections and reconstructions are ideally carried out on geological sections with equal vertical and horizontal scales. In some cases, as discussed above, it may be desirable to attempt to balance geoseismic sections where the vertical scale is given in two-way time. It is probable that the results of such an exercise will inevitably be inferior to a correctly balanced geological section where all of the geological information is observationally correct or the interpretation has a high degree of confidence. Geoseismic sections, however, invariably contain geometric information, in particular of deep events below the target formation which may be absent from the interpreted section and which give some qualitative control of the geometry. In addition the iterative application of balance techniques, particularly area, bed-length and fault trajectories derived from roll-overs on the hanging walls of listric faults are an essential part of the primary interpretation of the seismic data. Waiting until the geophysicist has depth converted his maps and derived true-scale geological sections from these may be too late. An interpretation which does not work geometrically may have already been built into the model. Attempts to balance sections should be made concurrently with the geophysical interpretation in order to maximize the evolving structural model.

EXTENSION CALCULATIONS

In extensional regimes it is also important to attempt to calculate depth to detachment for the basement faulting. Application of crustal models, such as those of McKenzie (1978a) and Le Pichon & Sibuet (1981), require that a brittle–ductile transition occurs at a depth of the order of 10–15 km. Where subsidence and extension values are required, regionally balanced sections are critical in providing a structural check on extension values calculated from the subsidence and thermal decay equations used in the McKenzie (1978a) model (e.g. Jarvis & Maclean 1980). These in turn may be important in maturation and subsidence history studies (e.g. Wood 1981). On a more fundamental level balancing regional lines for successive time intervals provides a direct test of the rapid stretching followed by thermal subsidence type of model. In many areas it is becoming clear that such a simple model, while adequate as a first order approximation, cannot be used in detail and that some cyclic stretch model may be more appropriate.

CONCLUSIONS

There are considerable benefits to be gained from improving structural interpretation in areas of extensional tectonics by the use of balanced section techniques. In particular, an improved understanding of the structural pattern and tectonic evolution of such areas can result if such techniques are integrated into seismic interpretation at an early stage. While seismic data rarely permit a unique interpretation of the structure, balanced geoseismic sections should be constructed iteratively in order to derive a geoseismic model which makes geometrical sense as well as obeying stratigraphic constraints. Care should be taken in producing models which are as simple as possible while honouring the data. The interpretational errors inherent in seismic data will infrequently allow ultra sophisticated analysis.

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