Conference Report

The geometry of normal faults

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This meeting took place at Burlington House on 14 and 15 June 1989. Until recently a specialist structural geology meeting on a theme such as this would have been solely the preserve of the Tectonic Studies Group. There is, however, currently much encouraging collaboration between industry and academia on research into all aspects of extensional faulting and thus this meeting was held under the joint aegis of the Petroleum Group and Tectonic Studies Group. The hope that such a meeting would draw participation from industry and academia was fulfilled, with the number of talks presented and the overall attendance dividing roughly equally between these two groups of Earth scientists. The programme included 31 papers and a number of poster displays; nearly 200 people attended.

Ultimately the proceedings of the meeting will, it is hoped, appear as a Special Publication of the Geological Society. The intention of this report is therefore not to review each contribution in turn, but rather to synthesize the main themes and conclusions of the meeting, in order that they should be disseminated into the Earth sciences community as rapidly as possible and prior to any future volume.

The recent involvement of industry in published basin analysis studies has resulted in an increase in the availability of seismic reflection data to all Earth scientists. A major emphasis at the meeting was therefore placed on what can be learnt about normal fault geometry from seismic reflection data. This main theme was amply supported by papers based on field studies, earthquake seismology and examples of quantitative modelling.

In recent years the literature on normal faults has expanded enormously, reflecting two major schools of thought pertaining to fault development: (1) that normal faults develop as linked systems of listric faults across the entire range of scales, (2) that normal faults develop as approximately planar dislocations which may or may not display direct physical linkage. Evidence that both end-member viewpoints have some practical importance was provided during the meeting through a large amount of high quality observational data. It was perhaps the main hope of ourselves, as convenors of the meeting, that the wide range of papers presented would allow some ‘ground-rules’ to be established to aid the interpreter in his choice of geological model. In this we believe the meeting was successful and we summarize below the consensus, although not necessarily unanimous, view of the conference.

Linked/detached extensional systems. Faults such as these appear to be confined to the sediment fill of an extended basin. No observational evidence was presented at the meeting which was able to demonstrate the existence of such faults (rather than infer their existence from geometric models) in either highly compacted sediments or crystalline basement. Detached faults are characterized by having strained hangingwalls but undeformed footwalls. They may be initiated by two quite distinct mechanisms: (1) gravitational collapse of a topographic high, such as a prograding delta, fault scarp or the unbuttressed sediment pile of a continental margin; these faults accommodate no basement extension, (2) distribution of basement extension into the cover via ‘easy-slip’ horizons, such as salt; these faults may be sited quite remote from their basement ‘root’. Gravity-driven (mechanism 1) faults are also frequently observed to ride on a salt detachment. A third category of detached faults, which need not necessarily link or be listric in form, are those which form in direct response to the upward motion of buoyant masses forming above structures such as salt and shale diapirs.

Planar faults systems. Planar faults (s.l.) are recognized from observational data in both the sediment-fill and basement of extended basins. Basement extension is accommodated on large, planar faults. Although low-angle planar faults (<30° dip) are recognized in highly-extended terranes, evidence is now coming to light that such faults may initiate at a higher angle of dip and rotate during extension. Angles of fault initiation are typically in the range 45–60°.

Planar fault systems may be treated on two broad scales, which in applied terms approximately equate with the exploration and production disciplines of the hydrocarbon industry.

On the large scale (major basin-bounding or fault-block-bounding faults) gravity plays an important role in the overall basin/fault geometry, and flexural/isostatic models appear to be the most appropriate. It is these faults which the exploration geologist will recognize as controlling or defining many hydrocarbon traps in extended basins. A particular feature of such faults, which is both observed and predicted quantitatively, is the uplift of footwall crests above sea-level. The amount of uplift scales with the size of the fault, and may be as much as 2 km adjacent to large faults in, for example, the North Sea. Isostatic compensation around normal faults becomes significant when the faults cut the entire ‘elastic/brittle’ upper part of the crust. Under normal continental geothermal conditions this requires the faults to extend to a depth of c. 10–15 km. Along-strike lengths of individual normal fault segments are typically 10–20 km, and the overlap zones between segments typically provide the main sediment routes into the basin. Normal faults with strike lengths greater than 10–20 km are probably formed from the coalescence of smaller faults.

On the smaller scale, faults contained entirely within the brittle upper crust (or ‘elastic lid’) have displacement geometries which correspond closely with dislocations across which successive elastic strains become locked-in as permanent strains. Several speakers emphasized this point by demonstrating that displacements vary smoothly within the fault surface from high values at the fault centre to zero.
at the fault-tip. Such faults, while perhaps not controlling hydrocarbon traps, are important to the production geologist, as it is these faults which partition hydrocarbon reserivors into separate compartments. These faults need not link physically to each other, but are able to produce strains over large areas because their displacement volumes overlap. Particular studies have shown that these faults, like earthquake ruptures, may be self-similar (fractal) in nature, and thus their size and displacement populations in all three dimensions may be governed by predictable relationships. Planar faults are characterized by reverse drag deformation of both the hangingwall and the footwall of the fault surface. Those faults confined within the ‘elastic lid’, however, by virtue of their smaller size, produce less footwall uplift than that predicted by flexural models of large-displacement faults. Furthermore, the wavelength of deformation relative to fault size is less for intra-elastic-layer faults than for through-going faults.

In addition to describing fault-style and faulting mechanisms, much has been published in the recent literature about the applicability of section-balancing techniques to extensional basins. This subject too was extensively covered at the meeting.

It now seems apparent that geometric section-balancing techniques, implying as they do no footwall deformation, are applicable principally to detached fault systems within the sediment fill of a basin. Even when such fault systems are ‘balanced’, great care is needed in defining the regional marker against which displacement is measured. Several speakers highlighted the complexity of hangingwall deformation and the inadequacy of vertical simple shear (‘Chevron construction’) in predicting the correct geometry for the fault plane. It seems that, in general, inclined simple shear provides the best approximation for the hangingwall deformation.

The application of geometric section-balancing techniques to planar faults, adjacent to which the footwall has deformed, will result in incorrect solutions to the problem of fault geometry. That is not to say, however, that such fault systems cannot be ‘balanced’, only that they cannot be balanced by the geometric techniques published at present. Instead, deformation must be balanced by restoring both hangingwall and footwall strain.

By its very nature this review is not an exhaustive account of the meeting, nor does it reflect the views of all participants. The opinions expressed here, however, received majority acceptance, and in order to aid seismic interpreters, together with others involved in basin analysis, we believe it to be important that they are made available to the geological community as soon as possible after the meeting.

We gratefully acknowledge all of the contributors at the meeting and hope that their views are satisfactorily synthesized here.

Papers presented in programme order:

R. Hardman (Amerada Hess) Invited introductory paper: The significance of normal faults in the exploration and production of North Sea hydrocarbons

M. Warner (Imperial College): Normal fault geometry, the contribution of deep seismic profiling

A. Beach, T. Bird (Alastair Beach Assoo) & P. Trayner (GECO): Structural geometry of faulting in the Nile Delta: Implications for hydrocarbon traps

T. Needham, R. Morgan (Robertson Group) & S. Matthews (BP): Development of superimposed normal fault systems, offshore and onshore N. Wales

G. Tsikos (University College London) & J. Dixon (Queen’s University, Ontario): Salt diapir geometry and normal faults—a perspective using the centrifuge technique

A. Koelsker (Geo–Recon) & W. Ehrmann (AWI): Geometrical expression of extensional features in faulted chalk overlying a salt diapir

M. Brightman, P. Jackson, J. Alexander, J. Hallan and others (BGS): Geophysical and hydrogeological techniques for fault evaluation: a case study of a shallow normal fault in south-west England

N. Kusznir & G. Marsden (Liverpool University): Rheological, thermal and isostatic constraints on normal fault geometry, applied to the Jeanne D’Arc Basin, Grand Banks

J. M. Holt & J. H. Rippon (British Coal): Examples of normal fault geometry from UK coal seismic data

T. J. Chapman & A. W. Menelli (GECO): The analysis of 3-D fault geometries and displacement gradients using an interactive seismic workstation

G. Yielding, M. Badley & B. Freeman (Badley Ashton): Seismic reflections from normal faults.

C. P. Peddy (BIRPS): Determining fault plane geometries from fault plane reflections using seismic modelling

D. Barr (BP): Relationships between faulting and sedimentation in semi-starved North Sea half-graben

J. Cartwright (Imperial College): The geometry and kinematic evolution of a major rift-bounding fault in the central North Sea

A. Roberts & G. Yielding (Badley Ashton): Deformation around basin-margin faults in the North Sea/Norwegian rift

A. Gibbs (Midland Valley Exploration): Linked fault systems: constraints of 2-D and 3-D balance

N. White (Cambridge University): A general method for determining normal fault geometries at depth

J. Hossack (BP Houston): Extensional section balancing and the Chevron construction

J. Wheeler (Liverpool University) B. Tørandbakken (Saga): Balancing techniques as applied to the Midgard Field, offshore Norway

A. Beach (Alastair Beach Assoo): The geometry of normal faults—examples from the Jurassic of Somerset

A. Koestler (Geo–Recon): Displacement modelling of a fracture zone recovered from an offshore core

C. Townsend (Geological and Tectonic Services): Fault geometry on Björnoya: a comparison between deep and shallow structures

S. Roberts (Cambridge University): Active normal faults in Central Greece and Western Turkey

L. Ward (Edinburgh University): The Polis Graben NW Cyprus—insights into the dynamism and evolution of linked extensional fault systems and anomalous footwall uplift from field studies and experimental models

M. Coward, R. Gillchrist & B. Trudgill (Imperial College): 3-D
geometry of Normal faults related to Mesozoic extension of NW Europe: examples from field studies in the French Alps

B. John (Cambridge University) & D. Foster (State University of New York): Ar/Ar thermal history of footwall rocks to a low-angle normal fault: constraints on fault initiation angles in the southern Basin and Range

W. Horsfield (Shell): Relationships between synthetic and antithetic normal faults

R. Westaway (Durham University): Distributed extension on active normal faults: observational evidence and theoretical models

J. Walsh & J. Watterson (Liverpool University): Kinematic coherence in arrays of normal faults

I. Van der Molen (Shell): Size, frequency distribution of normal faults

J. Jackson (Cambridge University): Block rotations in extensional regions