Numerical modelling of basin evolution, with application to southwest New Zealand

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Abstract

Observations of deforming sedimentary basins, from geological and tectonic studies, have been placed within a coherent geodynamic framework using two- and three-dimensional numerical modelling. The models consider the effect of rheologies, active faults, geometry and structural permeability on the deformation and deformation-induced fluid flow of basins undergoing compression. Modelling has shown that the position of deformation and uplift within a basin in a compressional environment is a function of the geometry of the basin, the strength of the basinal sediments, and the location of active basement faults. Fluid flow within the basin is driven by topography and controlled by the permeability. Where permeability is a function of the amount of strain, volume or shear, fluid flow is controlled by the location of the deformation and the volume response of the material to deformation.

Sedimentary basins formed in southwest New Zealand during the middle to late Cenozoic as a result of the propagation of the oblique transform boundary between the Australian and Pacific plates. These basins have hydrocarbon potential, including gas seeps, and are currently the focus of a major exploration programme. Numerical modelling, as described in this paper, can provide insights into material deformation and driving forces for fluid flow within such basins. It allows the inclusion of mechanical considerations in the analysis of the basin's potential as hydrocarbon sources, conduits and traps.

Introduction

Geodynamic modelling using two- and three-dimensional finite difference techniques has been used to investigate the deformation of sedimentary basins such as those found in southwest New Zealand. These models consider the effect on deformation of rheology within a deforming basin, of the tectonic boundary conditions, of the effects that the mechanics of the system may have upon fluid flow directions and the creation and destruction of permeability associated with deformation. By using a fully coupled mechanical/fluid flow approach, the effects on the system of rheology, tectonic boundary conditions, and permeability structure are considered. This study began with models of generic basins and then applied the techniques and interpretations to the basins of southwest New Zealand.

Tectonic setting of the southwest New Zealand basins

In the south of the South Island of New Zealand, the Australian/Pacific plate boundary runs out to sea and wraps around the southwest corner of New Zealand as the oblique Fiordland subduction zone (Davey and Smith, 1983) (Figure 1). During the Cenozoic, the portion of the plate boundary through southwest New Zealand has acted dominantly as a transform (Sutherland, 1995).

Accretion of terranes during the Cretaceous has led to major discontinuities within the lithosphere of southwest New Zealand. During the Cenozoic plate boundary evolution, these features have been reactivated and they have exerted a strong control on basin development (Norris and Turnbull, 1993). The basin sediments reflect the composition and tectonic movements of the crustal blocks in response to distributed strain adjacent to the plate boundary (Norris and Carter, 1982).

The sedimentary basins of southwest New Zealand are bounded by the basement blocks of the Fiordland Complex in the west, the Brook Street terrane in the east and the Caples terrane in the north (Norris and Turnbull, 1993). The boundaries between the basement blocks are major tectonic features developed during the Mesozoic Rangitata orogeny and which have been reactivated during Cenozoic tectonism.

During separation of New Zealand from Australia and Antarctica in the late Creteaous, extension led to the deposition of fluvial sands and coal measures in south-west New Zealand (Norris and Turnbull, 1993). During the late Eocene-early Oligocene, tectonic actively on the Moonlight and Hollyford fault system (Figure 1) led to the formation of marine basins east of Fiordland which continued to subside into the early Miocene (Norris and Turnbull, 1993). In the late mid-Miocene, tectonism was compressional leading to

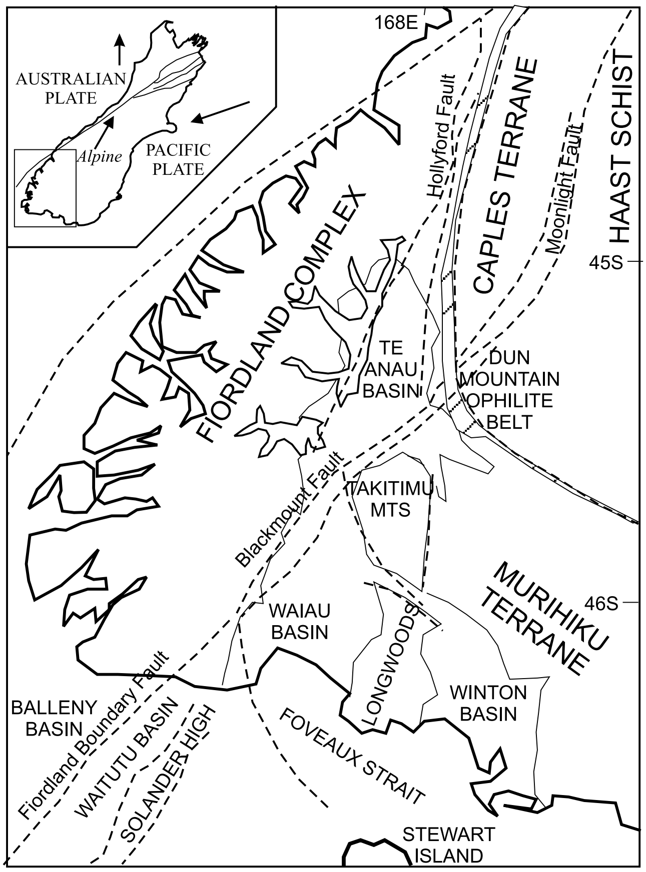

Figure 1: Locality map of southwest New Zealand showing the major basement terranes and the main structural features. Modified from Norris and Turnbull (1993). Inset shows the study area, the Alpine Fault and the relative plate motion between the Australian and Pacific plates.

reverse and possibly strike-slip faulting and folding in the southwest. The reverse faulting loaded the basins and caused further subsidence (Uruski and Turnbull, 1990).

Geodynamic modelling

Modelling techniques

The mechanics of basin evolution and associated fluid movement have been investigated by numerical models in two and three dimensions using finite difference continuum codes FLAC and FLAC3D (Cundall and Board, 1988; Itasca, 1997; Itasca, 1999). The modelling approach is to use simple models to isolate those processes which may be important for focussing and trapping fluids. By considering processes individually, their importance can be accessed. Later in this study, contributing processes will be combined into more complicated models and their relative contributions to fluid migration and/or fluid trapping will be analysed.

In the present study, the materials used in the models are described by a non-associated elastic-plastic material which is based on a Mohr-Coulomb yield condition and flow law (Vermeer and de Borst, 1984). Fault zones have been included into the model by using a weaker material. Fluid flow was modelled in two dimensions as flow through a permeable/porous medium which obeys Darcy’s Law.

The models investigated localisation of fluid flow with deformation and the development of structural permeability. Permeability in the models was made a function of the shear strain or the volumetric strain and the effect of these dependencies on fluid flow patterns was monitored.

Numerical models

Two-dimensional models of basin inversion

The two-dimensional numerical model is of a layered basin (Figure 2A). The basin is 8 km deep at the western end, 6 km deep in the east and is 50 km long. It is bounded by two normal faults, although these faults are only active in some of the models. Two west dipping faults in the basement beneath the basin are included in some of the models. The basin is filled with inter-bedded layers of soft mudstone and more rigid sandstone and in a variety of experiments is compressed to 5% shortening. The models are listed in table 1.

Fluid flow in two dimensions, models of basin inversion

Model 2 was used as a basis for the fluid flow experiments. Fluid parameters were imposed on the lithologic units so that the basement was relatively impermeable, 10^{-18} m^2, and the sandstone was more permeable than the mudstone, 10^{-15} m^2 and 10^{-16} m^2 respectively. The volume response of the material with deformation, the dilation angle, was varied between positive and negative values. Positive dilation angles correspond to material which expands with deformation while a negative dilation corresponded to a material which compresses with deformation, such as material undergoing compaction.

The volume response of structural permeability with deformation is modelled by allowing the permeability of the sandstone to increase to 10^{-14} m^2 and the permeability of the mudstone to increase to 5×10^{-14} m^2 with increasing volume strain or with increasing shear strain rate.

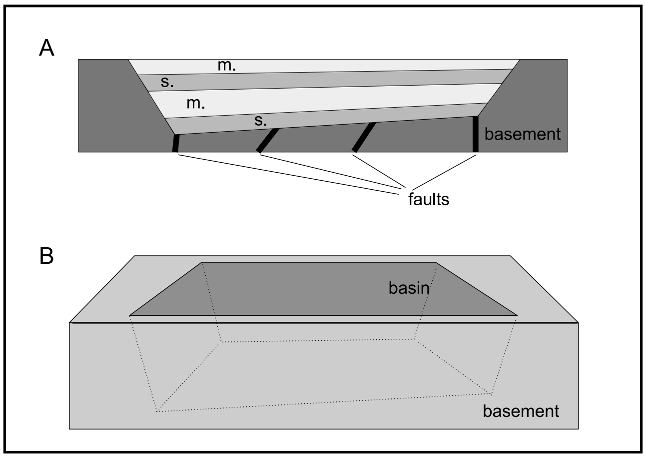

Figure 2: Schematic diagram of the models. A. The two dimensional model showing the lithologic units and the faults (m. - mudstone, s. - sandstone). B. The three dimensional model showing the geometry of the basin within the basement rocks.

Model 1	2D	No active basement faults
Model 2	2D	Vertical western boundary fault
Model 3	2D	Vertical eastern boundary fault
Model 4	2D	Both boundary faults vertical
Model 5	2D	Both boundary faults vertical plus west dipping basement faults beneath the basin
Model 6	2D	Eastern boundary fault vertical, western boundary fault dips to the east plus west dipping basement faults beneath the basin
Model 7	2D, wet	Vertical western boundary fault, permeability doesn't change
Model 8	2D, wet	Vertical western boundary fault, permeability is a function of the amount of volume strain that occurs with deformation
Model 9	2D, wet	Vertical western boundary fault, permeability is a function of the amount of shear strain that occurs with deformation, once permeability increases it doesn't change
Model 10	2D, wet	Vertical western boundary fault, permeability is a function of the amount of shear strain that occurs with deformation, transient changes
Model 11	2D, wet	Vertical western boundary fault, permeability is a function of the amount of shear strain that occurs with deformation, transient changes. Basinal sediments decrease in volume with deformation
Model 12	3D	Basin is deep in the west and narrow in the north. No active basement faults

Table 1: Description of the main points of the models discussed in the text.

Three dimensional model of a generic basin

All basins vary along strike and generally the compression direction is not orthogonal to the axes of the basin. Thus three-dimensional models yield a variety of information which cannot be obtained from two-dimensional models. The two-dimensional model was extended into three-dimensions as a basin bounded on all sides by basement blocks (Figure 2B). The basin is deeper in the west and narrows to the north and is inter-layered soft mudstone and more rigid sandstone as it was in the two dimensional models. The basin is deeper in the west and narrower in the north. The model was compressed from the west.

Results

Two-dimensional mechanical models

The first set of experiments considers how compressional deformation is taken up within an inter-layered basin for different fault geometries. If faults are not active (model 1, Figure 3A), compression results in movement on conjugate shears, causing uplift of the deepest end of the basin. Deformation is diffuse, particularly within the weaker internal mudstone unit which thickens while the sandstone layers fold. This creates an anticlinal structure in the top layers of the basin.

Active basement faults affect the deformation of the basin depending on where they are located. An active fault at the western edge of the basin (model 2, Figure 3B) focuses the deformation along the western edge of the basin, giving steeper topography on this edge and uplifting the whole basin sequence. The anticlinal structure is obvious through the whole depth of the basin, unlike model 1 where only the top layers formed an anticlinal structure. An active fault at the eastern edge of the basin (model 3, Figure 3C) causes approximately half the shortening and uplift to occur at the eastern edge of the basin, the remaining half still occurs within the basin at the western end, as for model 1. If both faults are active (model 4, Figure 3D), nearly all shortening and uplift occur in the west.

The inclusion of west-dipping basement faults beneath the basin dominate the deformation. Where the basin bounding faults are vertical (model 5, Figure 3E), the uplift occurs on the western inter-basinal basement fault and an anticlinal structure forms in the centre of the basin. Where the western basin bounding fault is dipping to the east (model 6, Figure 3F), some of the uplift is shifted east onto the second west-dipping inter-basinal basement fault. This results in two anticlinal structures at depth in the basin which turns into a broad anticline across the whole basin near the surface.

Fluid flow in two dimensions

Fluid was added to model 2 to investigate the effect of varying permeability on fluid flow within the basin (Figure 4). If permeability remains constant with deformation (model 7, Figure 4A), fluid is driven mainly by topography and flows through the more permeable sandstone units. There models were then modified so that the permeabilities of the sandstone and mudstone units were a function of the strain, either the volume strain or the shear strain. In model 8 (Figure 4B), the permeability increases as the volume strain increases. Flow is concentrated along the western boundary of the basin, with fluid driven downward by the topographic high and creation of volume within the shear zone by the deformation.

A similar pattern develops when the permeability increases as a function of the strain rate reaching a threshold value (model 9, Figure 4C). In this model, the permeability remains high even if the strain rate drops again. In model 10 (Figure 4D), the permeability increase with increasing strain rate is transient, that is, permeability is only high if the strain rate is high. Again flow is downward along the western boundary of the basin.

When the volume response to deformation of the basin sediments is to contract, flow is out of the basin. In model 11 (Figure 4E), the material is contractant but the permeability of the basinal sediments increases with increasing strain rate. Flow is directed upward and is concentrated into the shear zone along the western edge of the basin. Some of the flow

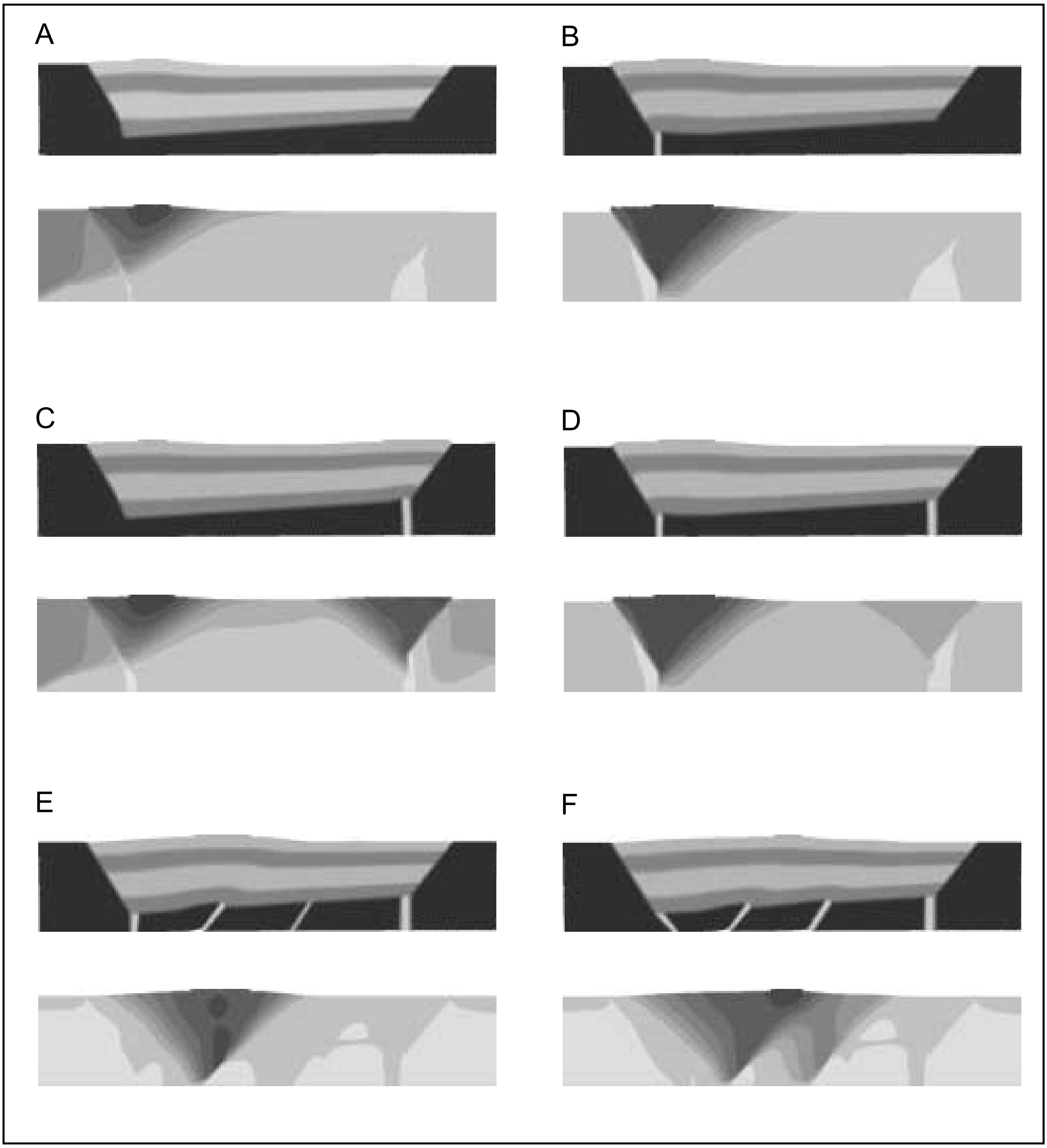

Figure 3: Models 1-6. The figure shows lithologic units and faults for each model and contours of vertical displacement (contour interval is 100 m, the maximum uplift is 700 m). A. Model 1 with no faults, B. Model 2 with a vertical western boundary fault, C. Model 3 with a vertical eastern boundary fault, D. Model 4 with both boundary faults, E. Model 5 with boundary faults plus west dipping basement faults beneath the basin, F. Model 6, as for model 5 but the western boundary fault dips to the east. See the text for explanation.

from this shear zone is then directed eastward into the upper sandstone layer. The presence of a seal above this unit would result in trapping of fluid within this sandstone layer.

Three-dimensional mechanical models

These models consider the effect of lateral geometric variations on the deformation within the basin (Figure 5). Uplift in the basin is greatest where the basin is the deepest, as was the case in two dimensions. As the basin narrows to the north, the amount of uplift increases as would be expected. Within the basin, an anticlinal structure which plunges to the south forms; the sandstone layers fold and the softer mudstone layers thicken and fold to a lesser extent than the sandstone layers.

Implications of the models for basin deformation

These mechanical and coupled mechanical/fluid flow models enable comment on a number of factors which are significant

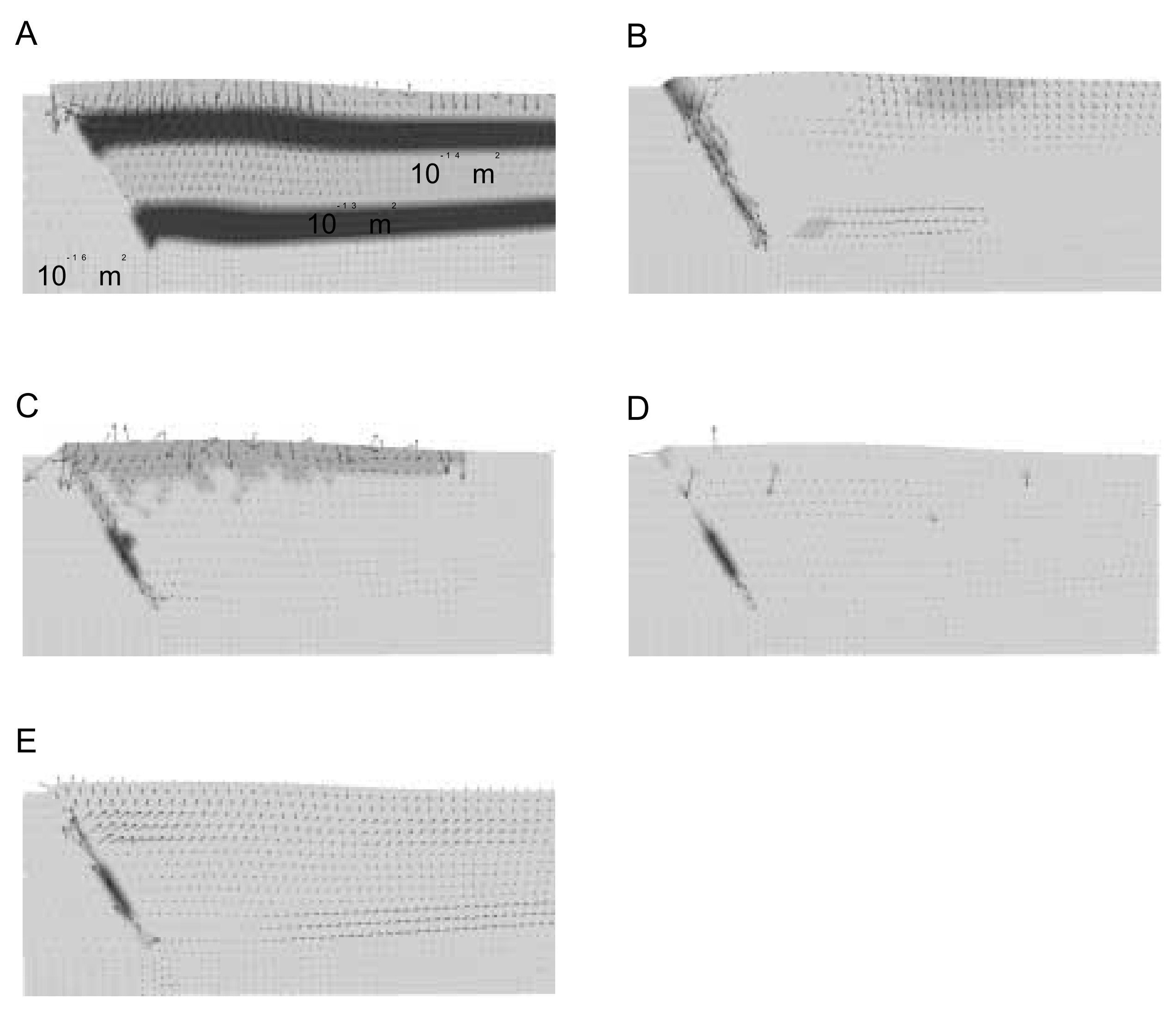

Figure 4: Models 7-11. The figure shows contours of permeability and fluid flow vectors for the western half of the basin. A. Model 7 in which the permeability of the different units remains constant. The maximum fluid flow vector is on the order of 0.03 m/yr. B. Model 8 where the permeability is a function of the amount of volume strain. The maximum flow rate is 0.2 m/yr. C. Model 9, permeability increases when the strain rate reaches a threshold value. Maximum flow rate is 2 m/yr. D. Model 10, permeability undergoes a transient increase when the strain rate reaches a threshold value. Maximum flow rate is 2 m/yr. E. Model 11, the basin sediments are contractant and permeability undergoes a transient increase when the strain rate reaches a threshold value. Maximum flow rate is 0.2 m/yr See the text for explanation.

for deformation of basin sand hence for their potential to trap and provide pathways for hydrocarbons. These include:

- how different basin units deform under compression;
- the effect of the basin geometry on basin deformation;
- the effect of active basement faults on basin uplift and deformation;
- how the volume response to deformation of the material and variable permeability structures affect fluid flow within a basin.

Sedimentary basins are often composed of layers of rock reflecting the varying sources of basin sediments, the water depths, and the sedimentation rates etc experienced by basins during their formation. These layers generally have different material and fluid flow properties, such as strengths, permeabilities and porosities. In the models presented here, the basins are composed of layers of rigid sandstones and softer mudstones. The changing material properties led to changing deformation patterns through the basin. The stronger sandstones tend to fold, forming obvious anticlinal structures under the imposed compressional boundary conditions. The softer mudstone units tend to thicken rather than fold. Although a mudstone unit above a folded sandstone will follow the stronger unit and fold rather than thicken.

These basins are often bounded by normal faults. These faults, or a new structure in their place, can be reactivated and inverted during the subsequent compressional deformation. Active faults on the boundaries of and within the basement, beneath the basin, had varying effects on the deformation within the basin. Anticlinal features formed within the basin above these faults, particularly above the west dipping faults

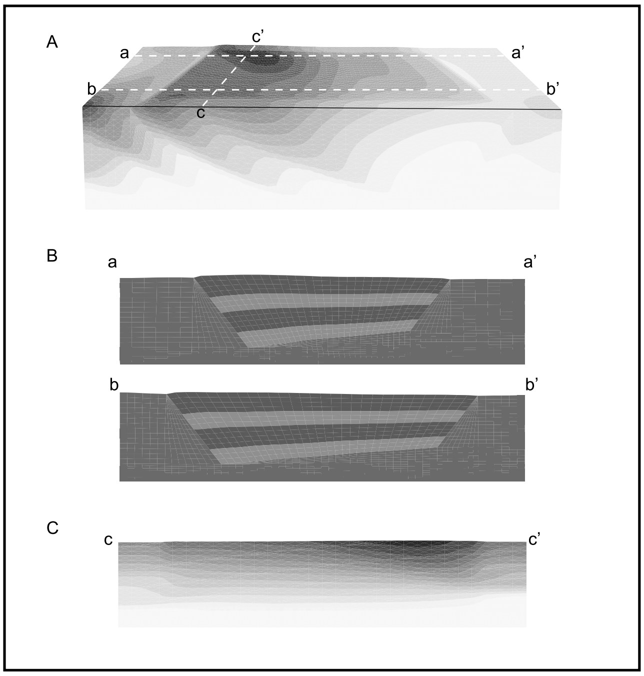

Figure 5: Three dimensional mechanical model of the basin. A. Block diagram of contours of vertical displacement (contour interval is 50 m, the maximum uplift is 600 m). B. Cross-sections of basin geometry after compression. C. Cross-section of vertical displacement along the length of the basin. Uplift is higher in the north.

in the basement. Such structures may be analogues for structures such as the Tuatapere Anticline in the Waiau Basin.

Fluid flow within the basin is controlled by topography, the volume response of the material due to deformation and the permeability structure of the basin. Where the permeability structure of the materials is unchanging with deformation, flow is controlled by topography such as in model 7 (Figure 4A). Flow is concentrated within the more permeable units and is downward. The downward flow is a result of dilatant basinal material which increase in volume with deformation. In the basinal material was contractant, flow would still be topographically driven and concentrated into the more permeable layers, but the general flow direction would be upward out of the basin.

However the permeability of the basin-fill materials is likely to change with deformation, leading to a dynamic permeability structure. In these models permeability was made a function of the strain, either the volume strain or the shear strain, such that permeability increased with increasing strain. Under these conditions, flow becomes concentrated along the western edge of the basin where most of the deformation is occurring (Figures 4B,C,D).

Observations from geological studies show the complexity and detail of sedimentary basins. These models are designed to isolate the fundamental characterisics of basins and processes of basin deformation which can lead to localisation of deformation, the development of structural permeability and the potential for transport and trapping of hydrocarbons. These simple models can be used to consider, for example, what the geometry of an anticline formed within the basin above a basement thrust fault will be. Such information can be used and compared with what is seen in the field, on seismics and in drillcores. Numerical modelling such as is described in this paper allows mechanical considerations to be added to other techniques of basin analysis and can provide insights into material deformation and driving forces for fluid flow that other techniques cannot.

These observations derived in the present and ongoing studies are essentially generic and hence have widespread applicability, not only to southwest New Zealand but to basins worldwide.

Acknowledgements

Mac Beggs, Glenn Thrasher and Shaun Hayton of Geosphere are thanked for helpful discussion about the Waiau Basin. Peter Koons read the manuscript and added to its clarity.

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