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Bathymetry sediment thickness and crustal structure from satellite gravity data

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Key Words: Bathymetry, crustal structure, inversion, New Zealand, satellite gravity, sediment thickness

ABSTRACT

Analysis of satellite gravity data offers an opportunity to rapidly evaluate the sedimentary structure of frontier basins. The accurate and evenly distributed measurements of the gravity field determined from satellite orbits contain information about the bathymetry, sediment thickness and crustal structure of the world's oceans. These data have been used by various authors, e.g., Smith and Sandwell (1994), to predict bathymetry for ocean basins where sediment cover is thin and where crustal structure is well known. In these areas, over a short wavelength band (15-160 km), the gravity field is highly correlated with the bathymetry. Along continental margins, however, the gravity field is complicated by sedimentary basins and changes in crustal structure.

The method presented here differs from previous techniques for analysis of satellite gravity data by inverting simultaneously for water, sediment and crustal thickness instead of decomposing spectral bands in the gravity field. The inversion is constrained by interpretations of seismic and other data, and by assumptions about the nature and spatial variability of the interfaces. The seabed, basement and crust/mantle boundaries are defined by a series of triangular facets, whose size varies as the amount of constraining data changes. The sediment/basement boundary and the base of the crust are defined by larger facets than those defining the bathymetry. Conditioning equations smooth the interfaces, make the depths tend towards the input values and ensure that the interfaces do not intersect. In areas of sparse bathymetric and crustal structural control a degree of ambiguity between long-wavelength shallow structures and short-wavelength deeper features inevitably remains.

This technique has been used to identify the presence and location of several sedimentary basins in an area 1250 by 1000 km west of New Zealand.

INTRODUCTION

Gravity surveys were one of the major contributors to petroleum exploration up until the early 1960's when seismic methods became dominant, due to the refinement of seismic techniques and to increasing demand for greater subsurface detail.

The oil and gas exploration industry has become increasingly interested in deep-water basins, often regions with few seismic lines and widely-spaced bathymetric data. However, the potential to obtain structural information about the continental shelves and margins has been enhanced by the availability of a uniform coverage of gravity anomalies over the oceans, derived from satellite-altimetry data (Sandwell and Smith, 1992).

Several studies have used satellite gravity data to predict bathymetry, e.g., Smith and Sandwell (1994). These studies generally use measured bathymetry along ships tracks to constrain the computed bathymetry, and use assumptions about the wavelengths of anomalies to implicitly account for the effects of changes in sediment or crustal thickness.

Smith and Sandwell (1994) used topography-gravity transfer functions at different spatial frequencies to isolate the bathymetry component of the satellite gravity anomalies. In sediment-free areas the transfer function should be flat, and a linear regression is appropriate. This works well on young seafloor, but is not as effective over old seafloor and continental margins where sediment cover complicates the simple correlation between gravity and bathymetry.

In the New Zealand region, Ramillien and Wright (1998) undertook a study in which they allowed for the crustal thickness variations by computing the deformation of the crust from the loading caused by the bathymetry. This technique also proved unsatisfactory in areas of thick sedimentary basins.

In this paper we discuss a technique to simultaneously model bathymetry, base of the sediments, and crustal thickness from gravity data, and present the results for an area west of New Zealand (Figure 1). The non-unique solution is constrained by interpretations of seismic and other data, and by conditioning equations that describe the nature and general shape of the interfaces. These equations determine how closely the interfaces must fit the control points, and the smoothness of the interfaces. Parameters for the conditioning equations are derived empirically.

THE MODEL

In this study, the Earth's crust is modeled as three layers defined by the seabed, base of the sediments and the base of the crust. The interfaces are defined by triangular facets, the size of each facet depends on its the proximity to the control points.

Defining the interfaces

Initial vertices defining each interface are points at which the depth of the interface is known. These may include the coastline (zero bathymetric depth), the boundary of exposed basement rock (zero basement depth) and depths measured from shipborne bathymetric and seismic observations. The accuracy of the depth of the interface at each point is indicated by a weighting factor; if some of the shipborne bathymetry points are more reliable than others then this variation can be allowed for without completely discarding the poorer quality information.

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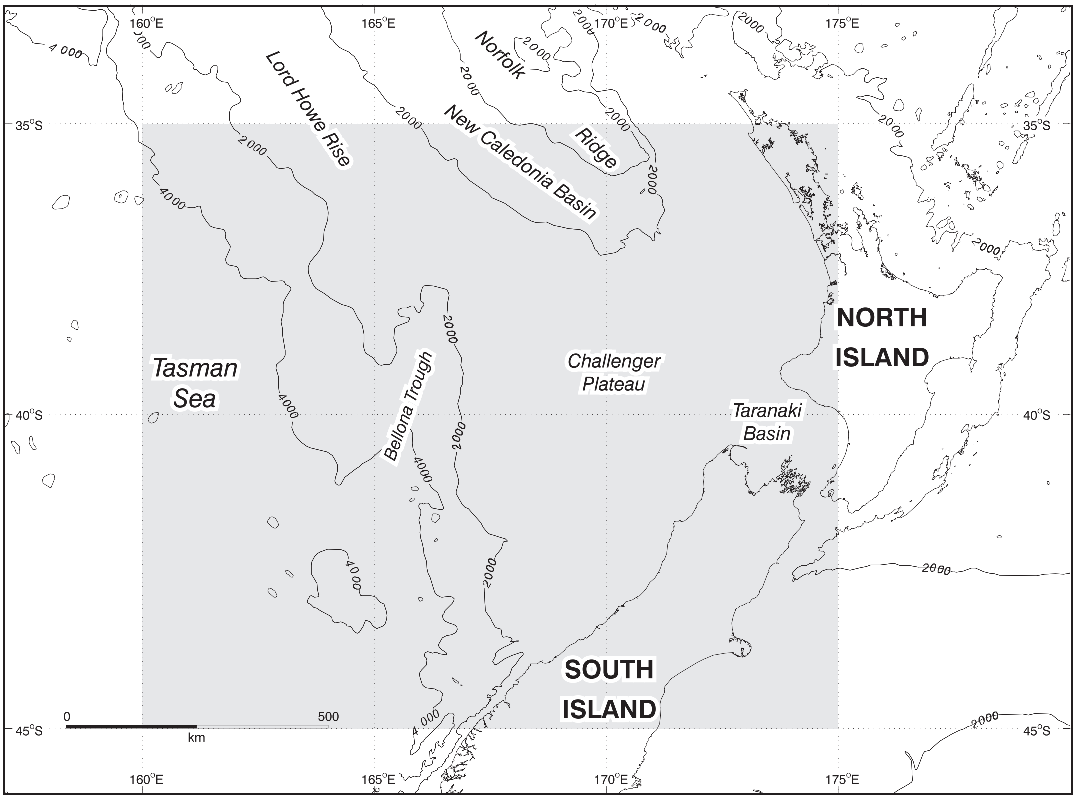

Fig. 1. Generalised bathymetric map of the Challenger Plateau and surrounding region. The area covered by the model discussed in this paper is shaded.

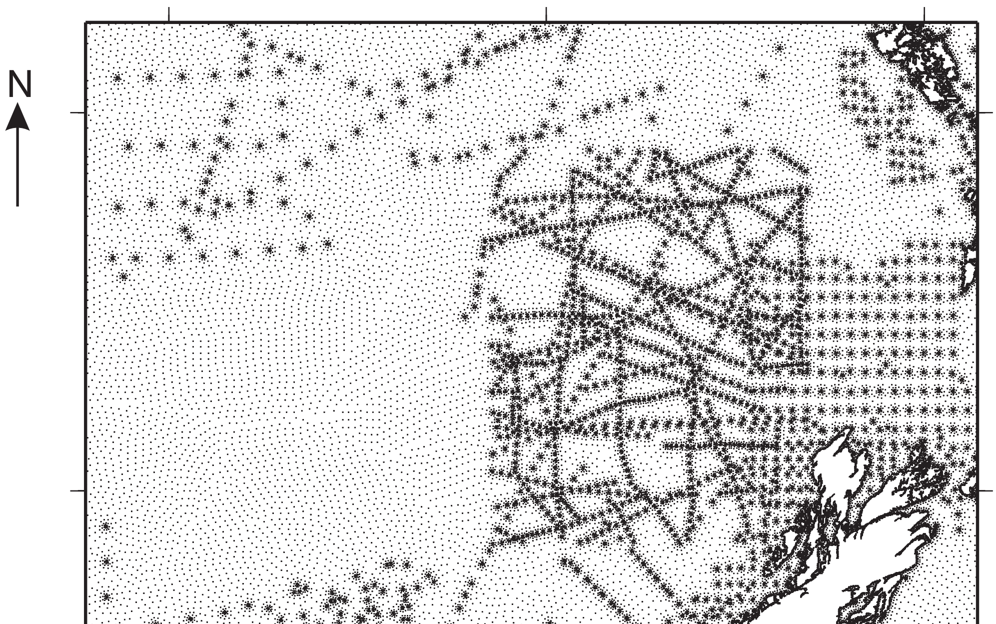

Fig. 2. The distribution of points defining the basement interface for the area over the Challenger Plateau west of New Zealand. The basement depths are known where exposed onshore, and offshore along ships' tracks and in areas covered by regional subsurface mapping. The grid of points is extended from these seed locations as described in the text, using a minimum distance of 1 km and a maximum distance of 8 km.

The initial points are weeded to give a set of points separated by a minimum distance (typically 500-1000 m). An iterative procedure is then used to fill in the gaps where the vertices are separated by more than the minimum distance. The procedure regularly increases the distance, up to a maximum, and inserts new points at locations where there is exactly one existing vertex within the specified distance. In this way the area covered by the vertices 'grows' away from the initial points and the density of points decreases way from the initial set of vertices. The detail that can be derived in the solution is, therefore, also reduced away from the control points. Figure 2 shows the distribution of computation points derived by this procedure for the basement interface in an area west of New Zealand using a minimum distance of 1 km and a maximum distance of 8 km. The initial points are readily recognised by the clusters of computation points, such as those associated with the area of exposed basement rocks onshore and the linear ships tracks offshore.

Having obtained the set of vertices the facets are defined using Delaunay triangulation (Wessel and Smith, 1998).

Gravity computations

Each interface is assigned a density contrast. The density contrasts across the interfaces may be determined as part of the solution, but the inversion is poorly determined and it is usually advisable to use *a priori* values for the density contrasts. The values used in this study are -1.3, -0.45 and -0.55 Mg/m^3 for the ocean/sediment, sediment/basement, and crust/mantle interfaces, respectively. These are equivalent to densities of 1.03, 2.33, 2.78 and 3.33 Mg/m^3 for water, sediments, basement and upper mantle, respectively.

Gravity anomalies were computed in this study, and each interface was assigned a standard depth that was used for calculating the volume of the layer between the standard depth and the interface. The standard depth for the bathymetry and basement was zero, and that for the base of the crust was 30 km. The gravity effect of the structure above the basement is calculated as a combination of the gravity effect of the water (using a density of -0.85 = -1.03 + 0.45 Mg/m^3) and of the combination of the water and sedimentary rocks (a density of -0.45 Mg/m^3). The value chosen for the standard depth of the base of the crust is not critical. It will modify the depth of this interface, but will have little effect on its shape.

The computation of the gravity effect of interfaces defining the bathymetry, top of the basement, and base of the crust close to the gravity observation points is performed using the algorithm developed by Woodward (1975) for the gravity effect of right triangular prisms. More distant parts of the interface are approximated by line sources. Both the gravitational attraction and its derivative with respect to the depth of the corners of the facets are computed so that variations in depth can be estimated using a linearised least-squares technique.

Equations to be solved

The depths of the vertices describing the interfaces, a regional gravity field (described by a polynomial) and the density contrast across each interface can be determined by the iterative solution of a set of linearised least-squares equations.

Three sets of equations are used: those derived from data, those that indicate the 'smoothness' of the interfaces, and those that are used to damp the solution at each iteration so that the depths move consistently toward a solution.

Equations derived from data

Two sets of data are available to determine the interfaces: measured depths at points on the interfaces and the satellite-derived gravity anomalies.

The equations relating the jth observed gravity anomaly value (go_j) to the changes in the current estimate of the depths of the vertices (Δz_i) are:

$$go_j - gc_j = \sum_i \frac{\partial gc_j}{\partial z_i} \Delta z_i \qquad (1)$$

where gc_j is the calculated gravity value for the current model at the jth point and the summation is over all the vertices.

The equation relating the measured bathymetry, basement depth or crustal thickness (b_k) to the incremental correction to the depth of the kth vertex (z_k) is:

$$b_k - z_k = \Delta z_k \ . \qquad (2)$$

Equations to ensure appropriate smoothness of the interfaces

The smoothness desired on the interfaces varies from location to location depending on the amount of independent data available for its definition. For example, it is undesirable to smooth the bathymetry in areas of good bathymetric control, but it is necessary in areas of poor bathymetric coverage. This variation is partly catered for by having the vertices defining the interface much closer together near the known control points. In spite of these constraints the depths of the vertices are grossly underdetermined. Additional 'smoothing equations' are introduced to alleviate this.

Smoothing is controlled by an equation that tends to minimise the variation in depth of the three vertices for each triangle. The weight applied to these equations is set *a priori* for each interface. The weight for the crustal thickness will tend to be greater than that for basement, i.e., the base of the crust will be smoother than the basement interface, and the smoothing weight for the basement interface will in turn be greater than that for the bathymetry.

Damping equations

Even with this conditioning, the equations are still generally poorly constrained. The iterative determination of the depth of the vertices is also damped, with the damping progressively weakened as a solution is approached.

Solving the equations

The set of equations formed by the above processes is large and in general poorly determined. The number of unknowns is the number of vertices of the facets forming the interfaces, plus the density contrast of each interface and coefficients of the regional gravity field if these are not fixed. Hence, even for reasonably small areas the number of variables may be 50,000 to 200,000. For the example used in this paper there were about 450,000 unknowns. These normal equations are not sparse as all the depths affect all the gravity observations; however, some of these interactions are very small. To form normal equations of this size is impracticable. To overcome this a 'reduced' set of normal equations is formed in which only a limited number of the largest coefficients in the full normal equations are used. The solution for each iteration is an approximation of the solution that would have been obtained if the full set of normal equations was used. Our tests show that the iterations move towards the least-squares solution.

AN EXAMPLE - CHALLENGER PLATEAU

The Challenger Plateau extends to the west of the North Island of New Zealand (Figure 1) and is thought to have a continental crustal thickness, e.g., Wood (1993 and 1994). It is bounded by the New Caledonian Basin and the Tasman Sea to the north and south, respectively. It extends to the northwest as the Lord Howe Rise. The area studied here is about 1,250 by 1,000 km.

Within this region shipborne bathymetric data (Figure 3) range from detailed hydrological surveys to sparse lines recorded by research vessels. Similarly, knowledge of sedimentary thickness ranges from areas that have been intensely surveyed for petroleum resources to those with very few poor-quality seismic reflection lines. There is little direct information of the crustal thickness, with data from six deep-crustal seismic lines contributing to the present study.

Bouguer gravity anomalies for New Zealand were used to extend the satellite free-air gravity anomalies onshore. The satellite free-air and onshore Bouguer anomalies were sampled on to 5 km and 4 km grids respectively.

Regional subsurface mapping (Isaac et al., 1994; King and Thrasher, 1996; Nathan et al., 1986; Wood, 1993) was used to constrain basement depth. The coastline and the basement outcrop map of New Zealand (NZ Geological Survey, 1972) were also used to specify the limits of the bathymetry and sedimentary sequences, respectively (Figure 3). The density of water, sediments, basement and mantle were assumed to be 1.03, 2.33, 2.78 and 3.33 Mg/m^3, respectively.

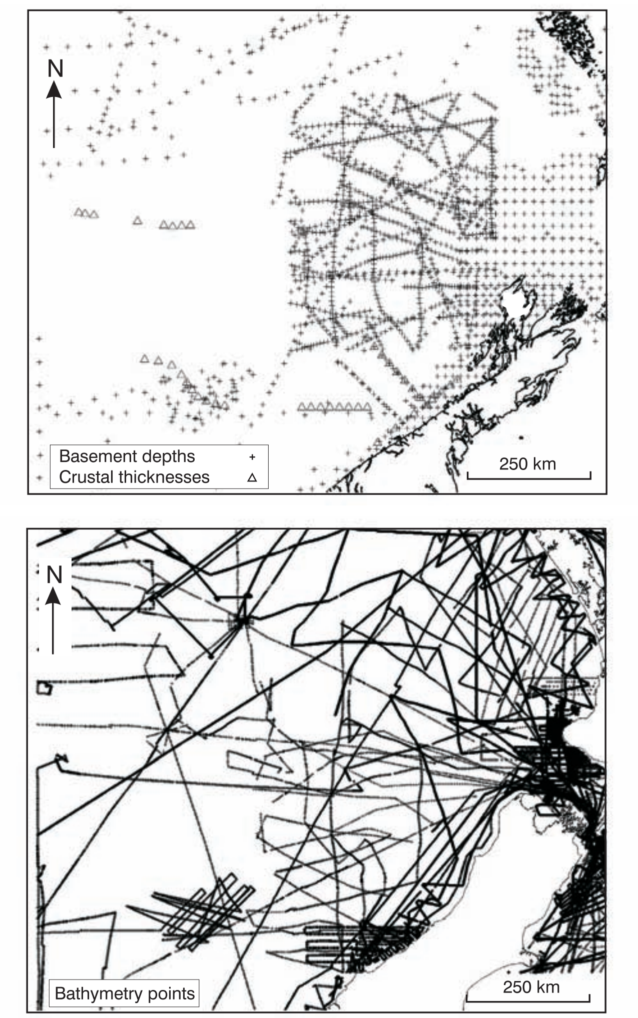

Fig. 3. The distribution of bathymetry (bottom map) and basement-depth (+) and crustal-thickness (_), (top map) measurements used to constrain the inversion of the gravity data. The satellite free-air and onshore Bouguer data were regularly sampled on 5 km and 4 km grids, respectively. Note in particular the unevenness of the distribution of the bathymetric data and the small number of crustal thickness measurements.

Meshes for the computation of the gravity effect of the bathymetry, basement and crustal thickness were generated using the measured depths as seed points. The distance between points forming the meshes were in the ranges 0.6-4.0, 1.0-8.0 and 10.0-30.0 km for the bathymetry, basement and base of crust, respectively.

The damped least-squares solution to determine the depth of the interfaces was performed for several iterations with the damping reduced as a solution was approached. The root-mean-square residuals in the gravity observations (difference between measured and computed anomalies) were less than 70 μN/kg (7 mGal).

MODELLING RESULTS

Figure 4 shows the bathymetry (bottom) and basement depth (top) computed for the area west of New Zealand. The Tasman Sea has depths of 5-6 km, the Challenger Plateau is less than 1 km deep and extends northwest as the Lord Howe Rise, and the New Caledonia Basin is 2-3 km deep.

Basement is relatively shallow along the northeast margin of the Challenger Plateau, deepening rapidly into the New Caledonia Basin. Basement deepens more gradually along the Challenger Plateau-Tasman Sea margin. Basement structure along this margin is blocky, reflecting the intersection of rift-related northeast and northwest trends. The northwest trends are parallel to spreading centres in the Tasman Sea, and the northeast trends are parallel to transform faults. The ridge to the west of the Bellona Trough appears to be mainly composed of sedimentary rocks.

The depth of the basement in the New Caledonia Basin (4,000-5,000 m) is similar to that of much of the Taranaki Basin on the North Island's western continental shelf. In this model there is no structural boundary between the New Caledonia Basin and the Taranaki Basin.

Sediment thickness, the difference between bathymetry and basement depth, is shown in Figure 5 (top). There are basins with more than 6 km of sediments along the continental shelf west of the North Island, and basins with more than 3 km of sediments extend at least 400 km along the New Caledonian Basin. Several locations of 2-3 km of sedimentary rocks are modelled along the western margin of the Challenger Plateau and Lord Howe Rise. A basin with 3 km of sediments is modelled on the Norfolk Ridge, 300 km west of the North Island.

The main feature on the map of crustal thickness (Figure 5, bottom) is the broad extension of New Zealand's continental block to the northwest. In the southeast, crustal thickening (to 38 km) under the Southern Alps in the South Island of New Zealand agrees well with estimates of crustal thickness for this part of New Zealand derived from onshore geophysical experiments, e.g., Davey et al. (1998).

CONCLUSIONS

Freely available gravity anomaly data derived from satellite altimetry data (Sandwell and Smith, 1992) can be used to estimate bathymetry, basement structure and crustal thickness over poorly surveyed areas of the continental margins. However, as with all potential field techniques, the results are non-unique and

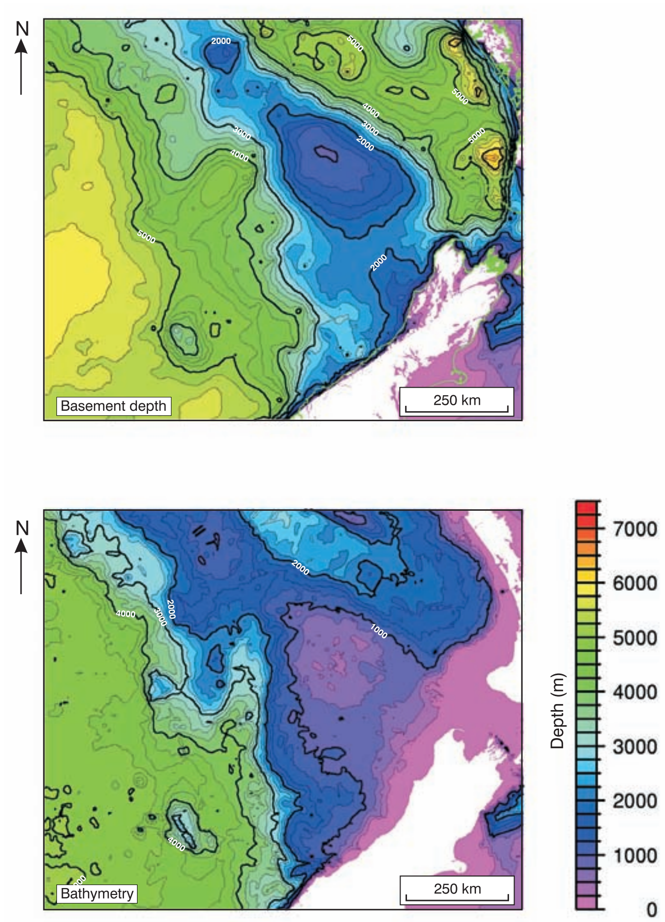

Fig. 4. Bathymetry (bottom) and basement depth (top) for the 1,250 x 1,000 km area west of New Zealand. The technique described in the text has been used to determine the shape of the sea floor, basement, and base of crust interfaces whose gravity response most closely matches the observed gravity anomalies.

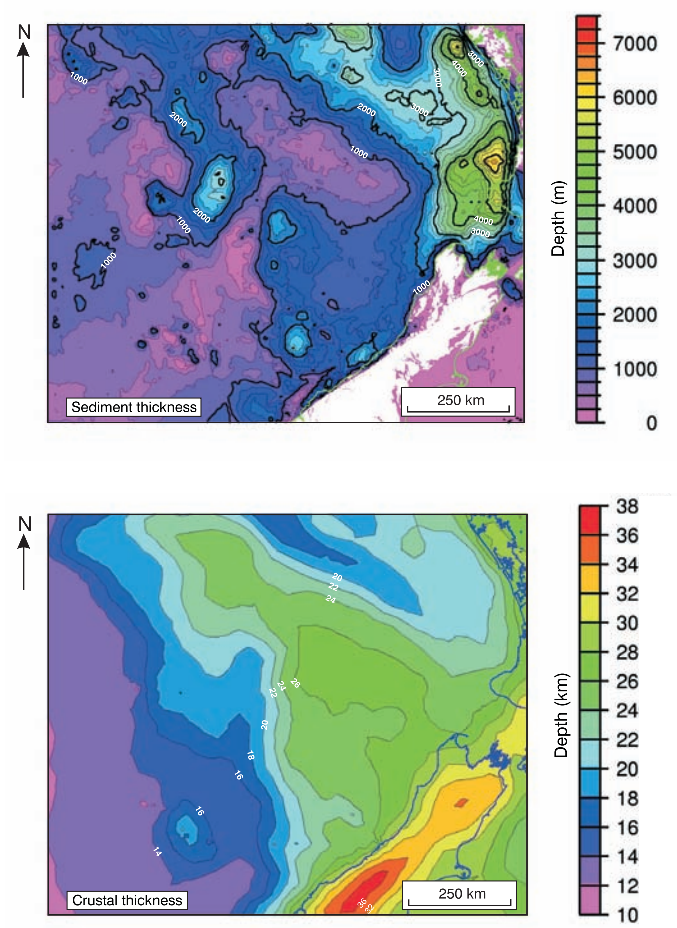

Fig. 5. Crustal thickness (bottom) and sediment thickness (top) for the area west of New Zealand determined by inversion of satellite gravity data. Crustal depth varies from 38 km beneath the Southern Alps in the South Island to 12 km in the Tasman Sea. The thick crust under the Challenger Plateau extends northwest under the Lord Howe Rise. The deep (>6 km) sedimentary basins west of the North Island extend 300-400 km down the New Caledonian Basin. A 3.3 km thick basin 100 km in diameter lies over the Norfolk Ridge, 300 km west of the North Island. The ridge to the west of the Bellona Trough is mainly composed of sedimentary rocks, and there are sedimentary basins 2.5 km thick along the southwestern margin of the Challenger Plateau and Lord Howe Rise.

bathymetry and other geophysical and geological data must be used to control inversion and evaluate the results. This technique provides a powerful tool for assessment of frontier basins in poorly surveyed areas.

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