ELSEVIER

Earth and Planetary Science Letters 206 (2003) 349–364

EPSL

www.elsevier.com/locate/epsl

Dynamic uplift in a transpressional regime: numerical model of the subduction area of Fiordland, New Zealand

Rocco Malservisi [a,*], Kevin P. Furlong [a], Helen Anderson [b]

[a] Geodynamics Research Group, Penn State University, University Park, PA, USA
[b] Ministry of Research, Science, and Technology, Wellington, New Zealand

Received 14 June 2002; received in revised form 6 November 2002; accepted 13 November 2002

Abstract

Bending of the downgoing plate in subduction zone typically leads to an offshore peripheral bulge. This leads to dynamic uplift generated by the elastic bending of the subducted slab, and is generally enough to support the topography of the bulge in a non-isostatic manner and produce a positive gravity anomaly. The Southwest region of the South Island of New Zealand, Fiordland, is characterized by high elevation and a large positive Bouguer gravity anomaly. This combination of high topography with high Bouguer gravity argues against isostatic equilibrium and suggests an additional support mechanism. Earthquakes as deep as 150 km, a deformed Benioff zone and inferences from plate reconstructions all support a tectonic model where the eastern margin of the Australian plate is subducting beneath Fiordland and is sharply bent. This bending of the Australian plate provides the needed non-isostatic support for Fiordland topography and generates the observed gravity anomaly. Although the peripheral bulge in subduction zones is generally localized offshore, the positive gravity anomaly (Bouguer and free air) in Fiordland is onshore, close to the shoreline, and generally corresponds spatially with high elevations. Here we propose a mechanism that allows the subducted sliver of slab to be decoupled from the main Australian plate and strongly bent beneath Fiordland. We test this scenario with a finite-element model. The model allows us to study the flexural response of a subducting elastic slab bent by lateral compression into a shape similar to the one inferred from seismicity. We test how different plate geometries and plate boundary forces influence the flexural dynamic support of Fiordland topography, providing important constraints on the local plate dynamics. The model results show that for a tectonically reasonable combination of plate geometries and boundary forces, the deformation of the lithosphere produces the observed topography and gravity signature. In particular we find that the bending of the subducted Australian plate can supply the needed uplift and support for the topography of Fiordland. However, a weak area west of but nearby the Fiordland shoreline, perhaps a fault or tear, is needed to decouple the subducted sliver, confine the bulge, and localize the uplift within Fiordland.

* Corresponding author. Present address: RSMAS-MGG, University of Miami, 4600 Rickenbacker Causeway, Miami, FL 33149-1098, USA. Tel.: +1-305-361-4928; Fax: +1-305-361-4632.
E-mail address: rmalservisi@rsmas.miami.edu (R. Malservisi).

0012-821X/02/$ – see front matter © 2002 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0012-821X(02)01100-7

Keywords: tectonics; dynamic uplift; gravity anomalies; finite-element analysis; subduction; Fiordland

1. Introduction

Plate bending in subduction zones typically leads to offshore uplift (peripheral bulge) with an associated positive free air gravity anomaly [1]. The subduction region of Fiordland (Fig. 1) in the southwest corner of South Island, New Zealand, is characterized by restraining bend geometry at the southern end of the Alpine Fault. Here the offshore bulge and associated gravity anomaly seem not to be present. Instead, the positive free air and Bouguer gravity anomaly are onshore and generally correspond with areas of high elevation. The Fiordland region is characterized by high elevation (> 1000 m) and a large positive regional Bouguer and free air gravity anomaly (> 150 mgal) [3] (Fig. 2). Earthquakes as deep as 150 km, a deformed Benioff plane [4–6] and plate reconstructions [7–9] support the concept that the eastern margin of the Australian plate is subducting below Fiordland with a sharply bent geometry. The occurrence of a significant positive Bouguer gravity anomaly (> 150 mgal) with regions of high elevation (> 1500 m) argues against simple isostatic compensation as the mechanism to support the topography (Fig. 3). Rather we propose that there is flexural dynamic support for the elevation of Fiordland, with that support derived from the sharp bending of the subducting Australian plate.

The South Island of New Zealand straddles the Pacific/Australian plate boundary (Fig. 1). Tectonically the area of Fiordland is characterized by the transition from a subduction regime along the Puysegur trench to a transpressive transform boundary along the Alpine Fault [9–11] (Fig. 1).

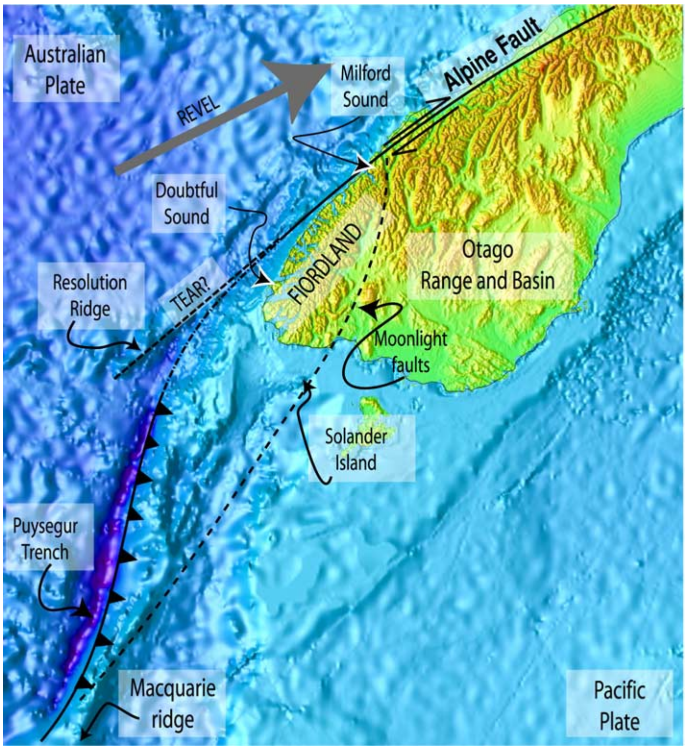


Fig. 1. Topo-bathymetry map of the southwestern corner of the South Island of New Zealand with the principal tectonic features of the region. The map includes the geographic references used in the text. Present day Au/Pa plate motion from REVEL [2].

Since ~5 Ma, migration of the Australian/Pacific Euler pole has produced an increasingly compressive component of relative motion along the plate boundary in the region of Fiordland and the Southern Alps [7,9]. Along the Alpine Fault, this increased compression has been accommodated through lithospheric thickening and the formation of the Southern Alps (e.g. [12–14]). In the area of Fiordland, because of the existence of a complex series of structures inherited from pre-

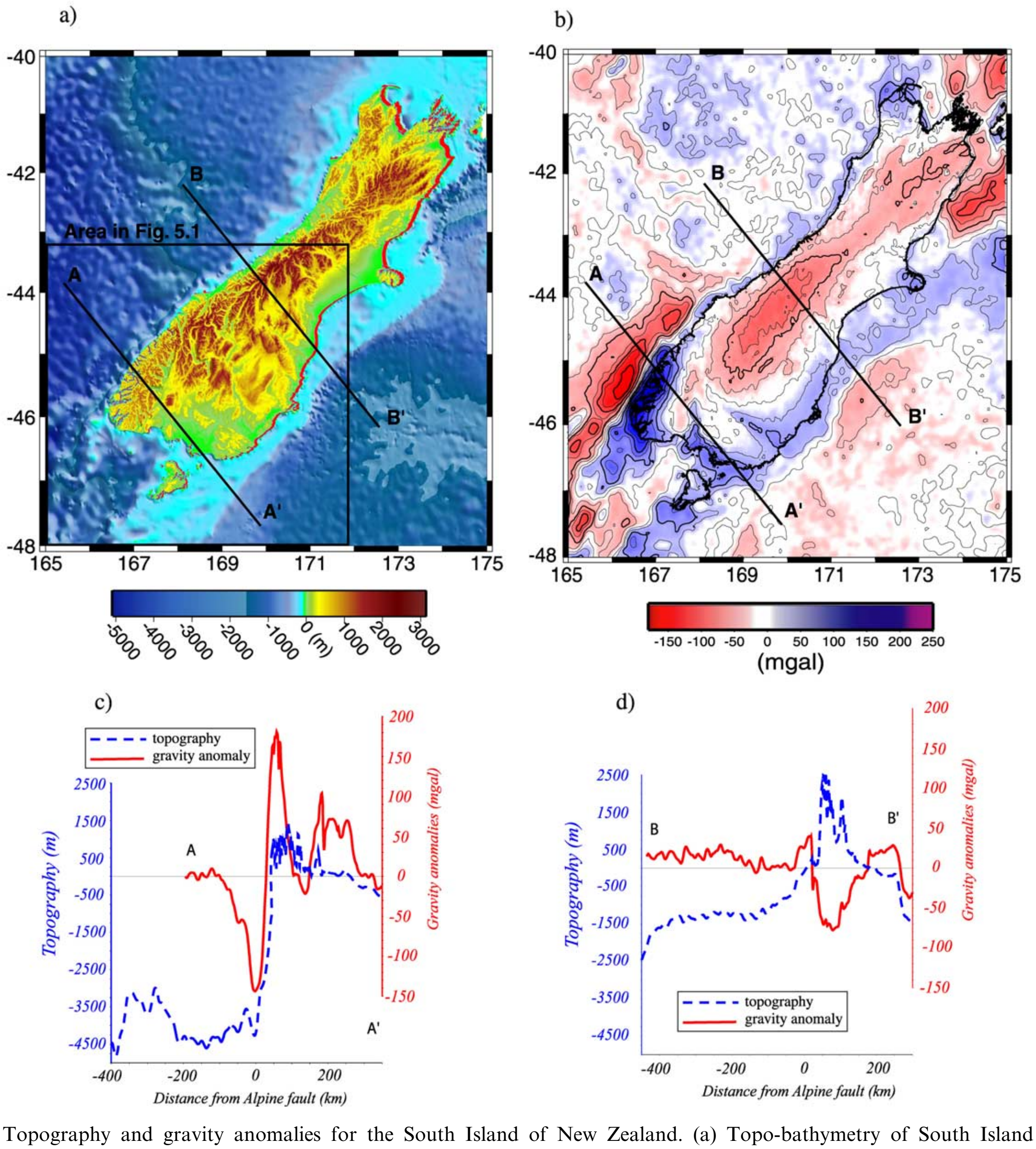


Fig. 2. Topography and gravity anomalies for the South Island of New Zealand. (a) Topo-bathymetry of South Island (from GTOPO30, http://edcdaac.usgs.gov/gtopo30/gtopo30.html). The box indicates the area of Fig. 1). (b) Bouguer (inland) and free air (offshore) gravity anomaly of the South Island [3]. Contours every 25 mgal. (c) Profile of gravity anomaly (red line) and topography (dashed blue line) across the Fiordland/Otago region (line AA′ in panels a,b). (d) Profile of gravity anomaly (red line) and topography (dashed blue line) across the Southern Alps region (line BB′ in panels a,b).

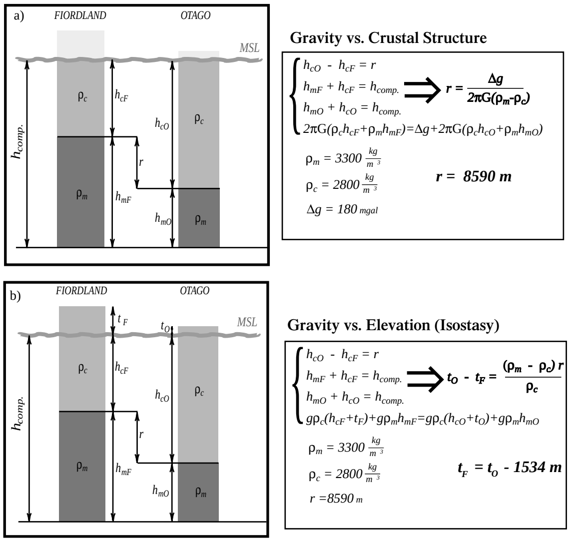


Fig. 3. Implications of gravity/topography observations for mechanisms of support. (a) A positive gravity anomaly is associated with dense material close to the surface. We assume a two-layer model with an upper layer (crust, light gray) of density ρ_c and the lower layer (mantle, dark gray) of density ρ_m. The area labeled Fiordland corresponds to the region with a Bouguer gravity anomaly of 180 mgal with respect to a reference region labeled Otago. In order to have that gravity anomaly, the dense material (mantle) must be $\sim$8500 m closer to the surface than in the reference region (Otago). The light layer above the mean sea level (MSL) is not included in the computation since we are computing the Bouguer anomalies. (b) Two regions are in isostatic equilibrium if the pressure due to a column of material is equal at the compensation depth. As in (a), we analyze a two-layer model of density ρ_c and ρ_m and we assume the density of the atmosphere to be equal to zero. Computing the isostatic pressure due to the column of material, we evaluate the difference of elevation between the two regions if they are in equilibrium. To be in isostatic equilibrium the average topography of the reference region (Otago) should be 1500 m higher than the Fiordland region. In reality, the average elevation of Fiordland is higher than the adjacent Range and Basin (see Fig. 2c), thus its elevation is not isostatically compensated.

vious tectonics regimes, transpression has led to the subduction of a corner of Australian plate [8,9] and to its localized bending [15].

Furlong et al. [15] suggest that the collision between the subducting Australian plate and the lithospheric root growing beneath the Southern Alps helped to initiate the bending of the slab and produced a sharp bend in the subducting slab. It is argued that the flexure of the Australian plate can generate the dynamic support onshore that uplifts Fiordland to its present elevation. In this paper, we test this hypothesis. We study the response of a bent elastic slab to the deformational forces produced by the interaction of the subducted Australian lithosphere with the lithospheric root that has formed beneath the Southern Alps of New Zealand.

An additional factor that may help to localize the dynamic support beneath Fiordland is a tear in the Australian plate adjacent to Fiordland. Bathymetric and seismic analyses [11,16] in addition to a flexural-gravity analysis south of Fiordland [16,17] argue that there is a tear in the Australian plate, essentially extending the Alpine Fault south-westward. Such a tear would decouple the subducting slice of the Australian lithosphere and greatly influence the subduction geometry. Previous work in other regions has suggested that the transition from a strike-slip regime to subduction can be facilitated by the presence of a tear in the downgoing plate (e.g. [18–20]). This may be important in the Fiordland region, where the highly deformed sliver of subducting plate and the presence of weak zone along the inactive Cretaceous passive margin east of the Alpine Fault–Resolution Ridge line [8] could serve to localize the mechanical decoupling. We analyze the role that such a decoupling zone, which for simplicity we refer to as a tear, can play in the dynamic support of Fiordland's high topography.

2. Slab geometry

We combine the observed pattern of seismicity and focal mechanisms to define the geometry of the subducting sliver of the Australian plate beneath Fiordland. The distribution of the seismicity as recorded by the New Zealand National Seismic Network [21] and a local portable network [5,6] shows a highly deformed Benioff zone. Offshore Fiordland, to the south, the Benioff plane is subhorizontal with an increase in eastward dip to the north (Fig. 4a–d). The Benioff zone is almost vertical beneath the northern part of Fiordland (Fig. 4b,d). At the northern end, the deep seismicity stops abruptly (in the area of Milford Sound) (Fig. 4a,b). North of Milford Sound, the seismicity is dominated by small, shallow events, with mainly strike-slip movement on planes subparallel to the Alpine Fault (e.g. event a) and not related to subduction.

However, the pattern of seismicity defining the Benioff zone is relatively diffuse, complicating the use of the seismicity alone to define the 3-D slab geometry. Whether this is simply a consequence of uncertainties in earthquake location, or the seismicity actually images a broad deformation zone associated with the sharp bending of the slab is uncertain. We favor the latter explanation, as a detailed microearthquake study in the region with good control in relative locations indicates a similarly diffuse pattern of seismicity [5]. In order to overcome this difficulty in using patterns of seismicity to define the plate boundary geometry, we combine the patterns of seismicity with the orientation of fault planes and slip vectors from the relatively large earthquakes in the region ($\sim M=6+$). We infer that these likely reflect plate-interface events (or they are near the plate interface) [22,23].

We assume that the larger events, particularly those with slip vectors compatible with present day relative plate motion, likely represent interplate earthquakes. Under this assumption, these earthquakes can be used to map the location of the interface between the two plates. This helps place constraints on both the geometry of the subducted Australian plate and the possible thickness of the overriding Pacific plate (Fiordland block). South of the Fiordland coast the main events lie at a depth of ~ 10 km (events 29,8,4,12 in Fig. 4a). The consistency in both orientation and depth of these events, and the alignment of their slip vectors with the plate motion direction suggests that the plate interface in this area is at a shallow depth and dips shallowly. Moving northward, the depths of the larger events increase to ~ 25 km (events 17, 27, and f in Fig. 4). This pattern of event depths suggests that the Fiordland block is less than ~ 25 km thick onshore (south of latitude 45°S) and that it thins moving southward offshore. The slip planes increase in dip both in the northward and eastward direction indicating a twisting of the interplate surface and an increased bend of the slab. The large event on the northernmost part (event g) is also the deepest (60 km) for which a well-constrained focal mechanism is available, and we interpret it to be an indication of the bending of the nose of the slab.

This is in contrast to the interpretation of significantly greater crustal thicknesses in that region (>40 km thick) recently proposed by Eberhart-Phillips and Reyners [24], in the vicinity of Doubtful Sound, from a local earthquake tomography study. We prefer our interpretation of a relatively thin Fiordland block (and as a corollary, a relatively thin Fiordland crust) as that is consistent with the pattern of seismicity, geological history, and the gravity pattern. The presence of thin crust in Fiordland is compatible with unroofing during the Cretaceous [25] that has led to the exposure of deep crustal rocks at the surface in Fiordland (e.g. [26]). Independent of the nature of the support mechanism, the large positive Bouguer gravity anomaly argues for very high-density material near the surface (e.g. [27]), consistent with a thin Fiordland crust. Additionally, if the Fiordland block were significantly thicker, the large earthquakes for which we have well-defined fault planes and slip vectors would reside within the upper plate and the subjacent plate interface would be essentially aseismic. We are not aware of any other subduction zones with a suite of plate-interface-like events that lie above an aseismic plate interface.

West of these subduction-interface events, there is a very interesting, and we think important, event – the Resolution Ridge earthquake (Fig. 4, event e). The depth and location of the event suggest that it is not directly associated with subduction beneath Fiordland. Furthermore, the slip vectors of both nodal planes are significantly different from the plate motion direction. Furlong et al. [15] have suggested that the event might be related to slip on the tear into the Australian plate.

3. Flexural model

To test the hypothesis that the sharp bending of

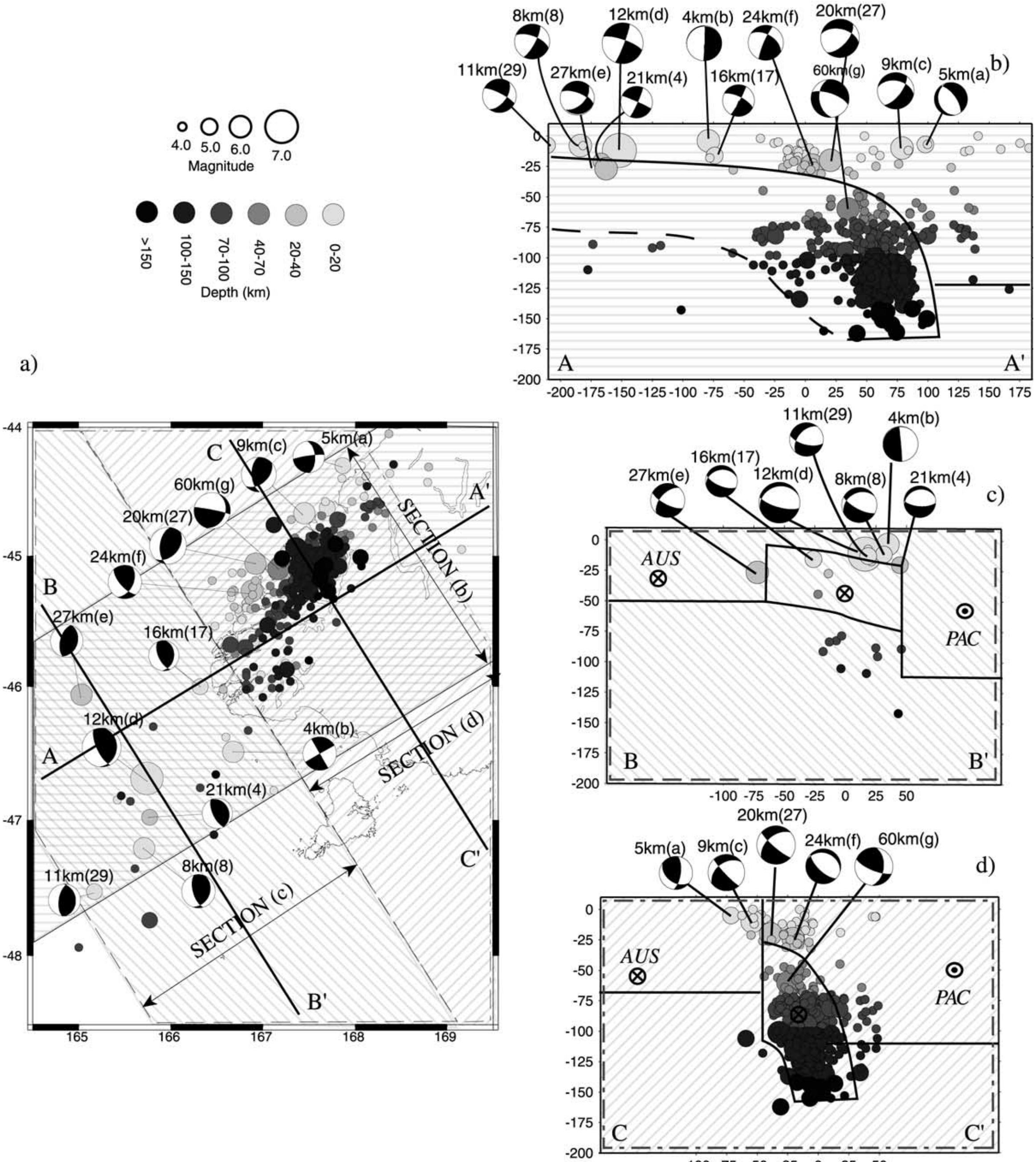


Fig. 4. Seismicity (1964–1998) from the NZNSN [21] and focal mechanisms in the Fiordland region. The local seismicity has been projected onto vertical cross-section planes (b–d). One cross-section plane is parallel to the plate motion (b) and two cross-section planes are perpendicular, a southern one (c) and a northern one (d). The shaded boxes in the map view correspond to the region mapped in the different cross-sections. The focal mechanisms on the map view (a) are a lower hemisphere projection while in the cross-sections are side projections on the plane of the cross-section. The focal mechanisms for the larger event in the area are labeled with the depth and a letter or a number corresponding respectively to the published solution [22,23].

the Australian plate beneath Fiordland can support the regional uplift and elevation pattern, we have analyzed the response of a bent elastic plate using a numerical model. We deform the lithosphere to a shape consistent with the geometry inferred from seismicity using the 3-D finite-element model code, TECTON [28,29,30,31].

The elastic thickness, elastic properties, and the forces applied to the plate are parameters that will influence the behavior of the slab and the resulting uplift and gravity. For an oceanic slab, the elastic thickness can be related to its age (e.g. [32]). The age of the subducted Australian lithosphere beneath Fiordland is not well constrained and falls in the range of 12–35 Ma [33,34,8,17]. This corresponds to a range in possible elastic thickness from 12 to 25 km. Here, we focus on the bending of a 13-km-thick elastic slab. This was chosen to be consistent with the plate reconstruction of Sutherland et al. [8], who argues for a relatively young lithosphere subducting beneath Fiordland. If the subducted slab is significantly older (greater elastic thickness) it will tend to deform on a broader wavelength, widening the uplift and pushing it further offshore. For the elastic properties, we used a Poisson ratio of 0.3 and a Young modulus of 40 GPa, typical values for oceanic lithosphere (e.g. [35]).

Fig. 5 shows the extent, geometry, and boundary conditions of the model. The elastic slab has a horizontal domain of 700×600 km^2, with the long dimension in the direction of the plate motion. Although the region of interest in this model is only approximately 300×200 km^2, we extend the southern and western extents of the model to minimize artifacts introduced by a no-displacement boundary condition applied along those margins.

We test the consequences of having the Australian plate interact on its northeastern corner with the thickening lithosphere of the Southern Alps to the north and the existing thicker lithosphere of the Otago Range and Basin [24] on the east. Our modeling strategy is to apply boundary pressures along the northern and/or eastern ends of the model, simulating the effects of this interaction with the root of the Southern Alps and/or the thicker/stronger lithosphere of Western Otago and Southland. The load of the Fiordland crust is also added to allow the computation of the actual topography and the induced gravity anomaly.

According to Furlong et al. [15], the increased compressive component of the relative motion between the Pacific and the Australian plates initiated the bending of the sliver of Australian plate already sitting beneath the Fiordland region. Following this hypothesis, a flat elastic slab has been deformed by the load of the Fiordland crust (Fig. 5b). This prestressed, deformed slab has been used as input for a new set of models where the slab has been further deformed by the pressure applied along the northeastern corner, simulating the interaction with the Australian plate. In order to avoid the instability due to the large element rotations and large deformations of the slab to the shape evinced by the seismicity, we deform the slab interactively, waiting at each time step for mechanical equilibrium before further deformation.

Starting with the slab deformed by the load of the Fiordland crust, we apply small pressures perpendicular to top surface of elements along the northeastern corner. Then we increment and reorient pressures perpendicular to the new direction of the top surface and apply the new pressure on the same elements. The process is repeated using the large-deformation formalism of Hall-Wallace and Melosh [36], recomputing the equivalent nodal loads corresponding to the stress vector for the current nodal position until the slab assumes a shape comparable with the observed one.

In all the processes, the forces introduced by vertical displacements of density contrasts (isostasy) (e.g. displacement of the surface or the Moho) are simulated using Winkler restoring pressures [37] applied at the top and bottom surfaces of the slab.

The presence of a tear or other decoupling weakness internal to the Australian plate can influence its flexural behavior (e.g. [16]). To analyze the role of such a detachment, we add to the elastic slab a tear implemented with the method of ‘slippery’ nodes [38]. These nodes behave as if they have been cut, allowing the two sides to have frictionless differential displacement (slip) on the defined surface. Such a fault, 150 km west of the 'collision' area, runs southward from the northern end of the slab, simulating the proposed propagation of the Alpine Fault into the Australian plate (Fig. 3) [16].

4. Dynamic topography results

We present two suites of model results: (1) a continuous Australian plate subducting beneath New Zealand, and (2) a similar plate geometry to (1) except with the addition of a 'tear', simulating the effect of mechanical decoupling in the plate.

4.1. Continuous plate

For the deformed continuous plate, when boundary forces are applied on both the northern (Southern Alps) and eastern (Otago) margin, the resulting uplifted bulge is oriented diagonally with respect to plate boundary orientation (Fig. 6a). This is inconsistent with the observed uplift pattern. To better match the plate-boundary-parallel observed pattern of uplift, we need to minimize the interaction with the Southern Alps lithospheric root. This would imply that the interaction with the thickening lithosphere of the growing Southern Alps does not significantly influence subduction beneath Fiordland.

The deformation of the slab resulting from an application of pressure only on the eastern side of the northeastern corner is similar to the inverted ploughshare model described by Christoffel and Van der Linden [4] (Fig. 6a), but even for a thin (13 km) plate the dynamic uplift (peripheral bulge) generated by the deformation poorly matches the observed topography. The uplift produced by this deformation is quite far away from the collision zone, offshore in the Tasman Sea, a region without high elevations or a significant gravity anomaly (Fig. 6b). Additionally, the resulting shape of the slab in the plate motion direction does not match the pattern of observed seismicity (Fig. 4).

a)

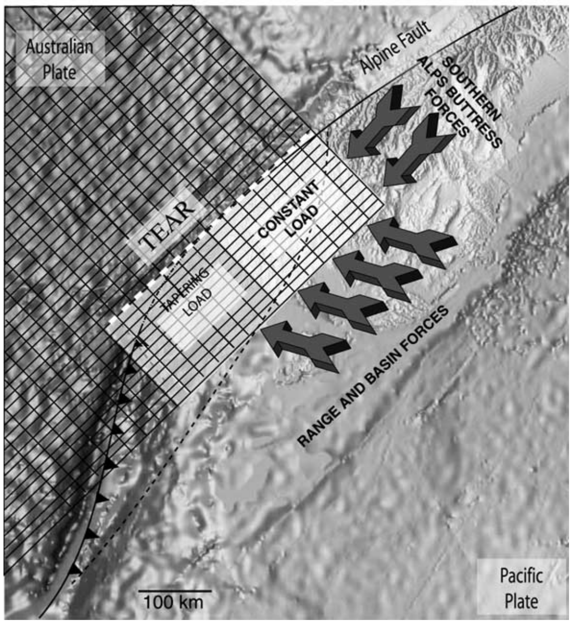


Fig. 5. (a) Extent of the model and boundary conditions. Elastic slab $700\times600\times13$ km^3 bent by incremental pressure applied along the northeastern corner of the model (big arrows). A vertical load applied on the light shaded area of the grid simulates the load of Fiordland. A tear (light dashed line) is added in some models to simulate decoupling of the subducting sliver from the main Australian plate. (b–d) Modeling method to compute the topography created by the dynamic support of the bent slab and the load of the Fiordland crust sitting on the subducting plate. Step 1 (b): To simulate the loading effect of 'Fiordland' necessary for the computation of the gravity signature, we computed the isostatic/elastic flexure equilibrium for a 13-km-thick elastic plate under a load sitting on the northeastern corner of the slab. In concert with the observed interplate seismicity and Fiordland extension, the block is 150 km wide and 300 km long with a density of 2800 kg/m^3 and is assumed to be 20 km thick in the northern part and taper to 0 southward. The effect of the Fiordland crust is simulated as a load sitting at the northeastern corner of the slab ('loaded slab') using the consistent load method (e.g. [45]). Step 2 (c): The prestressed 'loaded slab' is bent to the shape inferred by the microseismicity distribution by incremental pressure perpendicular to the top surface on the elements along the northeastern corner. ('total displacement'). Step 3 (d): The final topography is computed adding the 'Fiordland' block over the total displacement solution. In this computation the Fiordland block is displaced vertically with respect to its isostatic equilibrium position wherever the total displacement gives a positive support.

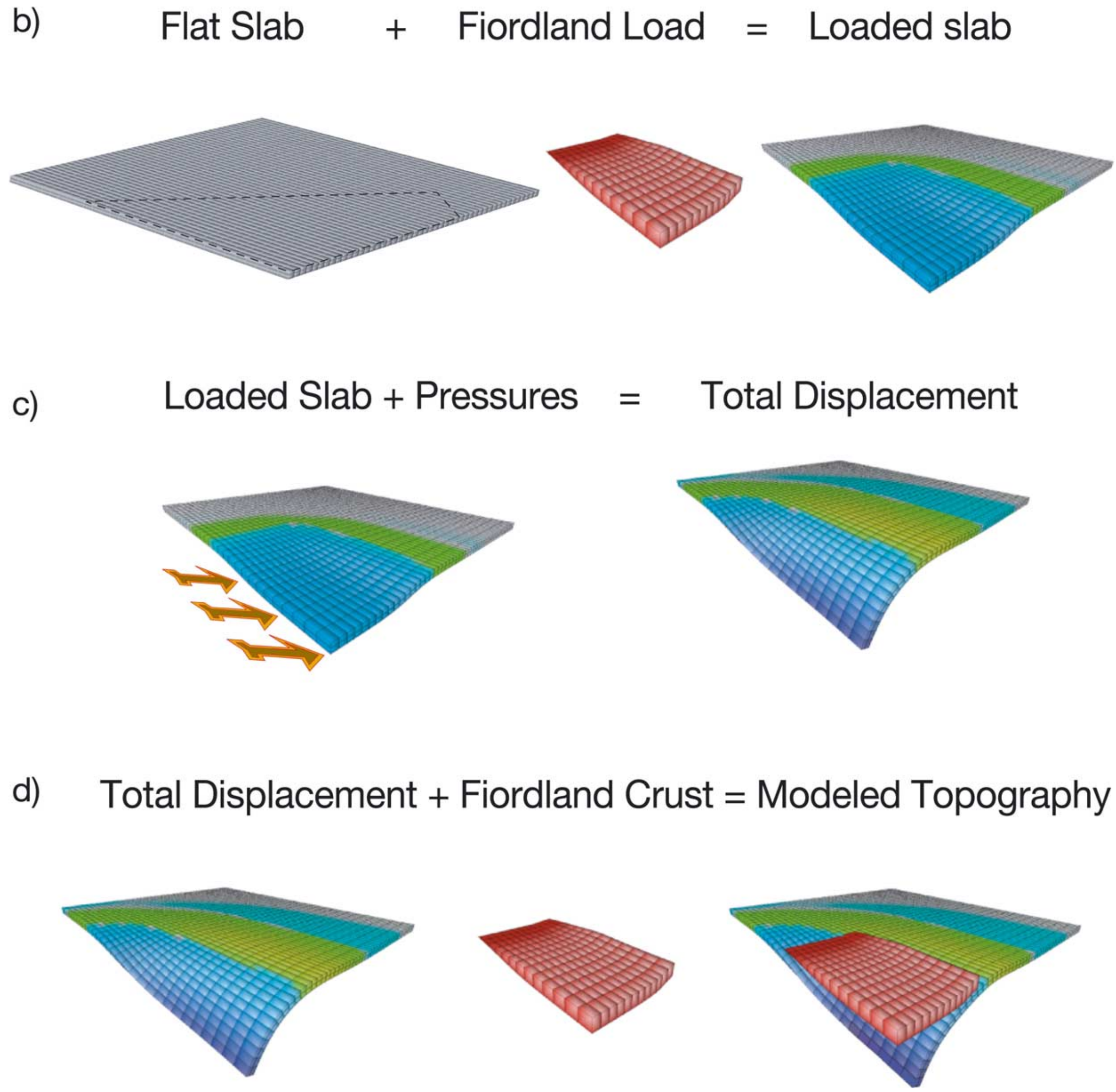


Fig. 5 (*Continued*).

4.2. Broken plate

The presence of a tear or weak area mechanically decoupling two sides of the Australian plate significantly changes the lithospheric dynamics of the Fiordland region. Although here we refer to the decoupling as a tear, mechanically the effects are compatible with any localized weak zone cutting the elastic portion of the Australian plate.

The tear decouples the deformation of the sliver of Australian plate east of the tear from the rest of the plate, removing the offshore bulge we see using models described in the previous section. For this case of a torn plate, an application of bending forces on the east is not sufficient to bend the slab into a geometry that matches the shape of the slab inferred from seismicity. If the only force that bends the slab is a pressure on the

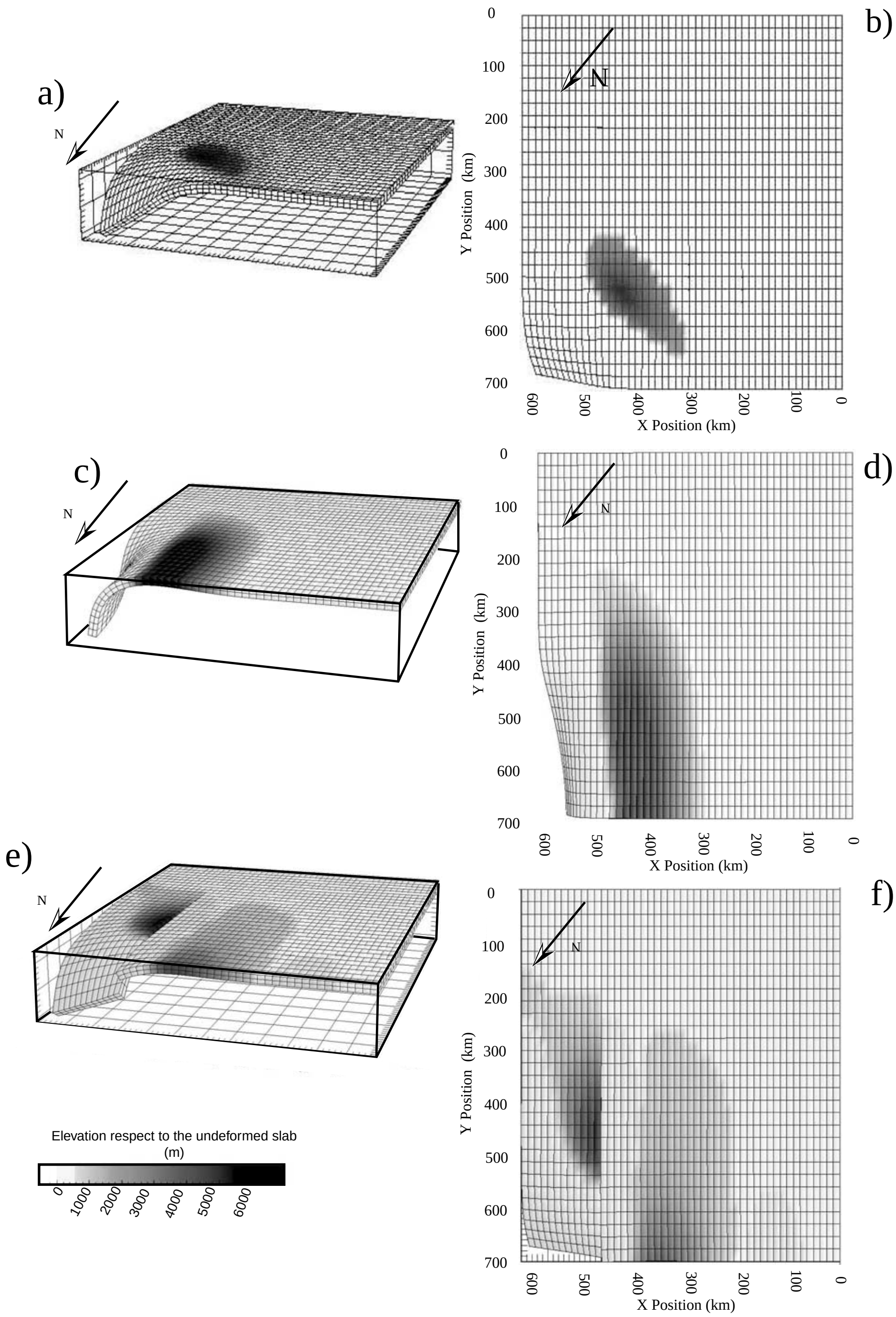


Fig. 6. Bent slab dynamic uplift with respect to the undeformed flat slab (Fig. 5b). The shaded areas correspond to the regions that have dynamic support. (a,b) Peripheral bulge for a continuous elastic slab deformed by pressures applied at the northern and eastern corner. 3-D (a) and map (b) views of the results. The 3-D view in all the figures is observed from the north (as for a hypothetical observer on the Southern Alps). (c,d) Peripheral bulge for a continuous elastic slab bent from eastern lateral pressures. (e,f) Peripheral bulge for an elastic slab with a tear decoupling the bent sliver from the main plate. The slab is bent applying both eastern and northern lateral pressures.

eastern side of the sliver of Australian plate, the flexural support increases from south to north, reaching the maximum at the northern end. Although the topography at the northern end of Fiordland is comparable or slightly higher than in the central Fiordland area, the absence of the positive gravity anomaly indicates that dynamic support for the topography at the northern end of Fiordland is not required. Furthermore, in this transitional area from Fiordland to the Southern Alps domain, the presence of a lithospheric root can support the topography and enhance the buttress effect. Since our goal is to analyze the gravity anomaly more than to match the topography, we prefer the model with the northern buttress. Incorporating the buttress effect of the lithospheric root of the growing Southern Alps to the north via pressure on the northern side of the slab, in combination with the effects from the applied pressure on the eastern side, improves the correlation of model predictions with observations. The application of pressure on the eastern side

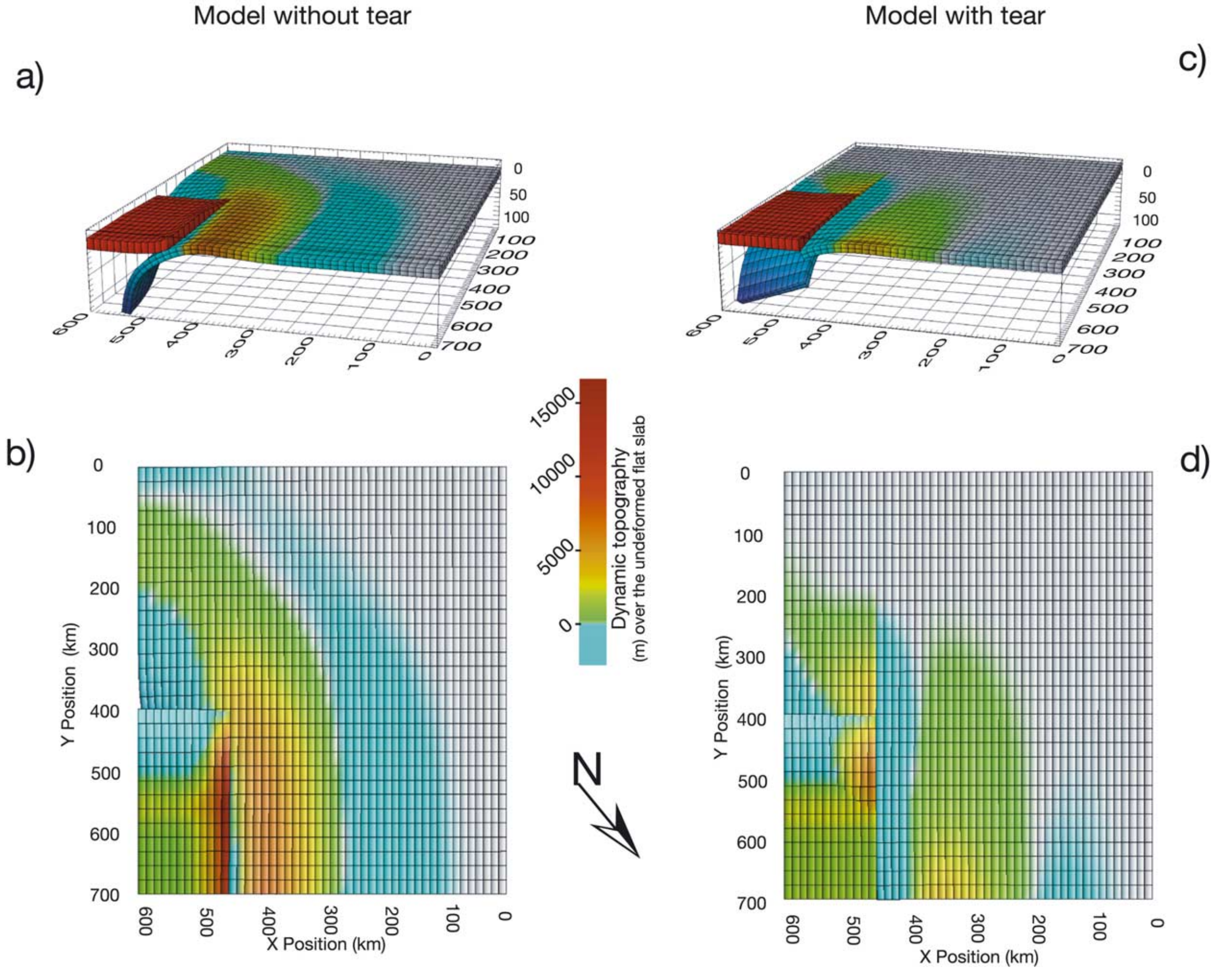


Fig. 7. Fiordland topography utilized for the computation of the gravity field. (a,b) Modeled topography for a continuous plate bent by eastern lateral pressure and loaded by the Fiordland 'crust' (see Fig. 5f). As in the previous figures the 3-D view is observed from the north. The map views show the combination of the topography due to the bent elastic slab and the supported crust. The elevation is plotted as vertical displacement with respect to the originally flat slab. To compute the gravity we assume an average ocean depth of 4500 m, thus we correct the computed topography by subtracting this amount. (c,d) Modeled topography for a broken plate.

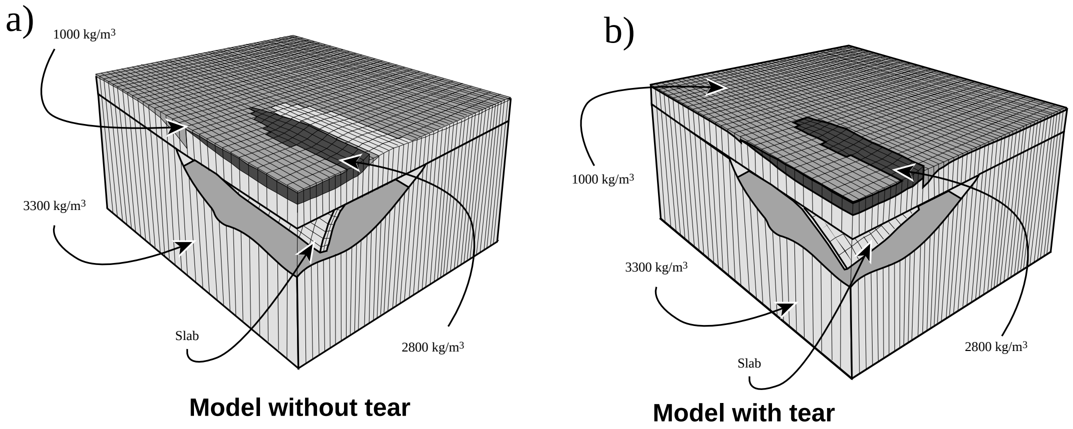


Fig. 8. Model utilized to compute the gravity field for a continuous elastic slab (a) and the broken one (b). A density of 3300 kg/m3 has been assigned to the region delimited by the top of the elastic slab or the bottom of the 'Fiordland' crustal block down to 150 km. The depth of the elastic slab in the area where it is not deformed is assumed to be 4500 m with water filling the vacant space. The Fiordland block is assumed to have a density of 2800 kg/m^3.

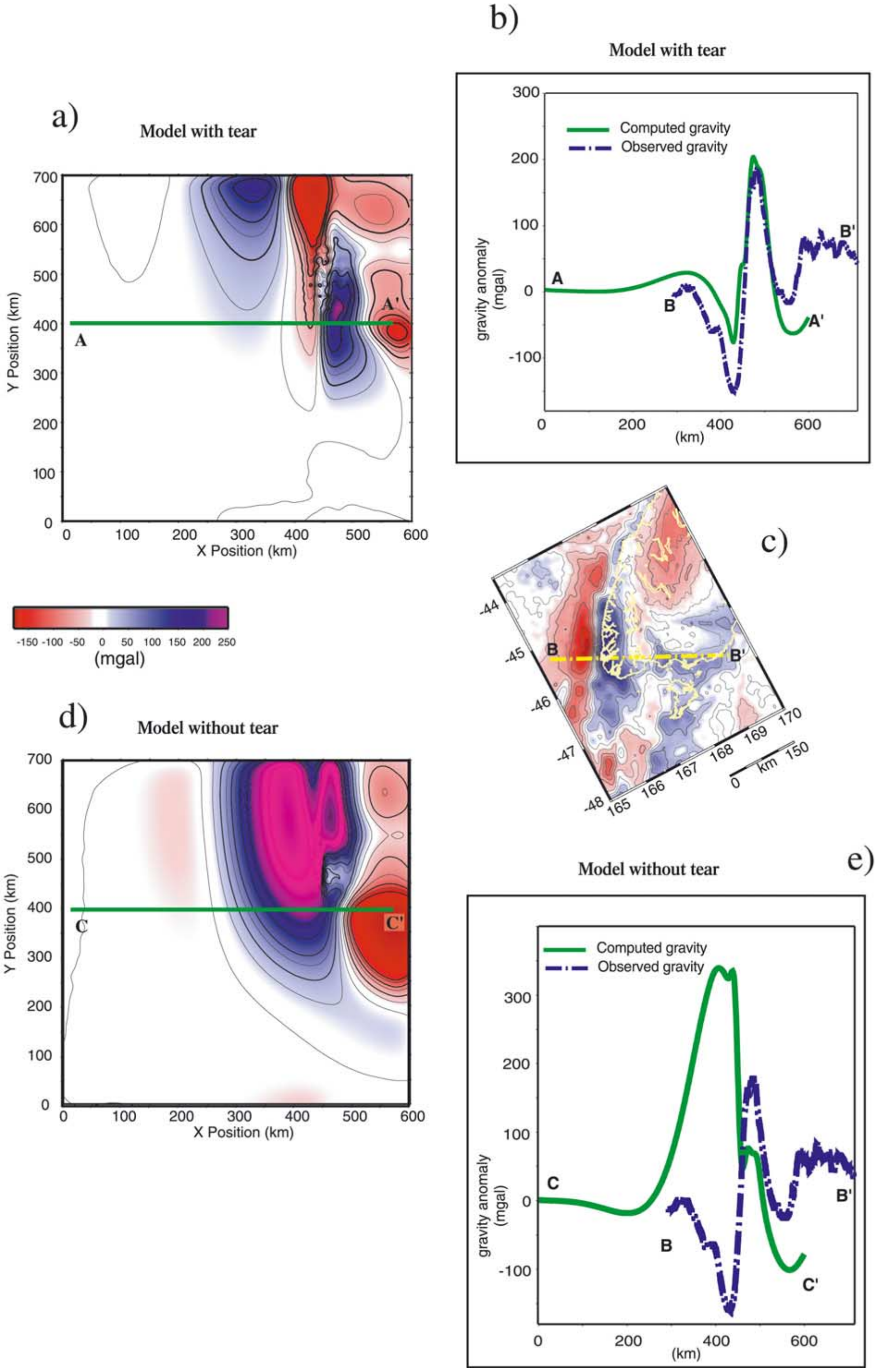
induces an easterly dip that increases from south to north, while the pressure on the northern side bends the tip of the subducting slab downward, increasing the northern dip and reducing the dynamic support in the northern section. This moves the predicted uplift in center coastal Fiordland. With these two pressures applied, the final geometry assumes a shape consistent with seismicity pattern. A subhorizontal slab is subducting at the Puysegur trench and is progressively bent, moving northward, increasing in dip both in the north and east direction to an almost vertical plane below northern Fiordland (Fig. 4). At the same time, the dynamic uplift generally reproduces the observed pattern of the topography (Fig. 6c). Furthermore, the presence of the tear introduces a preferred orientation in the bulge direction that follows the eastern side of the fault/tear in a pattern compatible with topography–bathymetry observations (e.g. [16,39,40]).

5. Gravity

A primary motivation for analyzing the role of the Australian plate flexure in producing the uplift of Fiordland was the pattern of gravity and topography. The association of the positive Bouguer gravity anomaly with the high elevations of Fiordland suggests that the region is not in isostatic equilibrium. Our modeling indicates that the flexure of a broken plate can provide the dynamic support to sustain these elevations. This section discusses the resulting gravity signature associated with the computed subduction geometry.

→

Fig. 9. Observed and modeled gravity anomalies in Fiordland. (a) Map view of the gravity anomalies computed from the model of Fig. 8b, broken plate. As in all the map views on this page, the contouring interval is 25 mgal. The positive anomaly close to the boundary in the north and the negative anomaly beneath the letter A′ are artifacts of the boundary conditions. (b) Comparison of the gravity anomaly computed for a broken plate along the profile AA′ of panel a (continuous line) with the anomaly observed along the profile BB′ of the map c (dashed line). (c) Map of the gravity anomalies observed in the Fiordland region. As in all the plots in this figure, we report Bouguer anomaly inland and free air anomaly offshore. (d) Map view of the gravity anomalies computed from the model of Fig. 8a, continuous plate. The negative anomaly beneath the letter C′ is an artifact of the boundary conditions. (e) Comparison of the gravity anomaly computed for a continuous plate along the profile CC′ of panel a (continuous line) with the anomaly observed along the profile BB′ of the map c (dashed line).


a)
Model with tear
Y Position (km)
X Position (km)
A
A'
(mgal)
b)
Model with tear
Computed gravity
Observed gravity
gravity anomaly (mgal)
(km)
A
A'
B
B'
c)
B
B'
km
d)
Model without tear
Y Position (km)
X Position (km)
C
C'
e)
Model without tear
Computed gravity
Observed gravity
gravity anomaly (mgal)
(km)
C
C'
B
B'

Previous gravity models [27] suggest that the gravity signature can partially be explained by juxtaposition of oceanic and continental crust at the coast. However, this effect by itself can only explain about one half of the anomaly observed in Fiordland. Walcott [27] suggests that the Fiordland block needs to be tilted up to the west and that Fiordland is considerably elevated above its equilibrium position. He proposed that the forces maintaining the Fiordland block out of isostatic equilibrium arise from the internal flexural rigidity of the plate. In contrast, we suggest that the vertical displacement of Fiordland is due to a dynamic support from the bending of the subducting Australian lithosphere. Since the Fiordland block is bounded by major fault systems (Alpine Fault in the west and Moonlight faults on the east), we prefer the concept of dynamic support over lithospheric rigidity. In order to compute the gravity field, we include in our models the effect of the Fiordland block as explained in Fig. 5. The resulting topography for the cases of a continuous and a torn plate are shown in Fig. 7.

The plate geometry, crustal structure, and elevations determined in the 3-D finite-element modeling are converted to an equivalent mass distribution for the gravity model. The modeled area (Fig. 7) is approximated with rectangular prism elements of prescribed density (Fig. 8). A density of 3300 kg/m^3 is assigned to prisms starting 150 km deep up to the bottom of the load in the region loaded by Fiordland (red prisms in Fig. 7) or to the top of the deformed elastic slab elsewhere. We also assume that undeformed slab at the southwestern corner lies 4500 below sea level. For this reason the topography in Fig. 7 is translated downward by this amount and replaced with prisms of the density of water. In order to eliminate edge effects, we include the region surrounding the model assuming that it has the same composition as the reference model (4500 m of water over oceanic lithosphere). The gravity signature is computed using the algorithm described by Nagy [41,42]. To generate the gravity anomalies, we subtract from the result the reference value obtained from the gravity signature of an infinite slab with the reference model density structure. We also apply a Bouguer correction to every point above the water level ($z = 0$ m).

Fig. 9 shows the results of the gravity computation for the continuous and broken plates. The offshore bulge created by bending a continuous plate generates a high positive gravity anomaly that is not present in the observed data (Fig. 9a). In contrast, the gravity signature for the broken plate model reproduces the wavelength, shape and magnitude of the observed gravity anomaly reasonably well, in particular, for the positive (onshore) side. The model underestimates the negative anomaly. Our model does not include the effects of the ~5 km of sediment in the Fiordland trench [39,43,44]. This would increase the downward deflection of the western side of the system, increasing the magnitude of the negative anomaly. In both models, the large negative anomaly in the eastern Otago region is simply an artifact of boundary condition effects as well as the positive anomaly offshore in the broken plate model.

6. Discussion and conclusions

Sharply bending an elastic slab to the shape of the Australian plate subducted beneath Fiordland generates a dynamic uplift. For the model of a continuous slab, the dynamic uplift is localized well offshore in the Tasman Sea in area where neither high bathymetry nor positive gravity anomaly are observed. A tear or a weak zone mechanically decoupling the subducting sliver of the Australian plate from the main plate eliminates the problem of the offshore bulge and confines the dynamic uplift beneath Fiordland. In this case, the dynamic uplift provides the necessary support to keep the Fiordland region in a non-isostatic equilibrium while creating topographic and gravity signatures compatible with the observations. We conclude that mechanical decoupling of the highly deformed sliver of the slab beneath Fiordland from the main Australian plate is consistent with the observed data. The nature of this decoupling is still not completely clear. A tear extending the Alpine Fault into the Australian plate as suggested by Lebrun et al. [16] is a viable candidate and would be compatible with the stress field determined by Reyners et al. [6]. Nevertheless, the lack of seismicity along such a fault [6] may argue for the decoupling to be a more diffuse weak region. At present, the available observations do not allow us to distinguish between these two models. Recent bathymetric and seismic data acquisitions on the area west of Fiordland [Barnes and Lamarche, personal communication (2001)] will hopefully allow us to refine the models and improve our understanding of this decoupling.

Acknowledgements

We thank Keith Kepleis, Martha Savage, and Charles Williams for thorough reviews of the manuscript and comments that greatly improved the paper. We are also grateful to C. Ammon, A. Nyblade, R. Engel, and T. Dixon for internal reviews of the paper and for their interesting suggestions. Rob Govers gave us the code TECTON as well as important suggestions and comments. During the work that led to this paper, R.M. and K.P.F. have been supported by grant NSF-EAR 97-25187. Many of the figures in this paper has been done using GMT [P. Wessel, W.H.F. Smith, New, improved version of Generic Mapping Tools released, EOS Trans. AGU 79 (1998) 579]. ***[SK]***

References

[1] A.B. Watts, Isostasy and Flexure of the Lithosphere, Cambridge University Press, Cambridge, 2001, 458 pp.

[2] G.F. Sella, T.H. Dixon, A. Mao, REVEL: a model for recent plate velocities from space geodesy, J. Geophys. Res. 107 (2002) 10.1029/2000JB000033.

[3] W.I. Reilly, C.M. Whiteford, South Island gravity map of New Zealand, N.Z. Department of Scientific and Industrial Research, Wellington, 1979.

[4] D.A. Christoffel, W.J.M. Van der Linden, Macquarie Ridge-New Zealand Alpine Fault transition, in: D.E. Hayes (Ed.), Antarctic Oceanography II: The Australian-New Zealand Sector, Antarc. Res. Ser. 19, AGU, Washington, 1972, pp. 235–242.

[5] M.Reyners, R. Robinson, Seismicity, Structure and tectonics of the fiordland region as revealed by a microearthquake survey, personal communication, 1995.

[6] M. Reyners, R. Robinson, A. Pancha, P. McGint, Stress and Strain in a Twisted Subduction Zone, Fiordland, New Zealand, Geophys. J. Int. 148 (2002) 637–648.

[7] R. Sutherland, The Australian-Pacific boundary and Cenozoic plate motions in the Southwest Pacific some constraint from GEOSAT data, Tectonics 14 (1995) 819–831.

[8] R. Sutherland, F. Davey, J. Beavan, Plate boundary deformation in South Island, New Zealand, is related to inherited lithospheric structure, Earth Planet. Sci. Lett. 177 (2000) 141–151.

[9] R. Sutherland, A. Melhuish, Formation and evolution of the Solander Basin, southwestern South Island, New Zealand, controlled by a major fault in continental crust and upper mantle, Tectonics 19 (2000) 44–61.

[10] J. Delteil, J.Y. Collot, R. Wood, R. Herzer, S. Calmant, D. Christoffel, M. Coffin, J. Ferriere, G. Lamarche, J.F. Lebrun, A. Mauffret, B. Pointoise, M. Popoff, E. Ruellan, M. Sosson, R. Sutherland, From Strike-slip faulting to oblique subduction: a survey of the Alpine Fault-Puysegur Trench transition, New Zealand, Results of Cruise GEODYNZ-sud Leg 2, Mar. Geophys. Res. 18 (1996) 383–399.

[11] G. Lamarche, J.F. Lebrun, Transition from strike-slip faulting to oblique subduction active tectonics at the Puysegur Margin, South New Zealand, Tectonophysics 316 (2000) 67–89.

[12] T. Stern, P. Molnar, D. Okaya, D. Eberhart-Philllips, Teleseismic P wave delays and modes of shortening the mantle lithosphere beneath South Island, New Zealand, J. Geophys. Res. 105 (2000) 21615–21631.

[13] P. Molnar, H.J. Anderson, E. Audoine, D. Eberhart-Phillips, K.R. Gledhill, E.R. Klosko, T. McEvilly, T.V. McEvilly, D. Okaya, M.k. Savage, T. Stern, F.T. Wu, Continuous deformation versus faulting through the continental lithosphere of New Zealand, Science 286 (1999) 516–519.

[14] Y. Shi, R.G. Allis, New insight to temperature and pressure beneath the central Southern Alps, New Zealand, N.Z. J. Geol. Geophys. 38 (1995) 585–592.

[15] K.P. Furlong, R. Malservisi, H. Anderson, Initiation (?) of subduction in a complex transpressional regime, Fiordland, New Zealand, Geophys. Res. Abstr. EGS 27th General Assembly, Nice, France, 2002.

[16] J.F. Lebrun, G. Lamarche, J.Y. Collot, J. Delteil, Abrut strike-slip fault to subduction transition The Alpine Fault-Puysegur Trench connection, New Zealand, Tectonics 19 (2000) 688–706.

[17] J.F. Lebrun, G.D. Karner, J.Y. Collot, Fracture zone subduction and reactivation across the Puysegur ridge/trench system, southern New Zealand, J. Geophys. Res. 103 (1998) 7293–7313.

[18] E. Calais, N. Bethoux, B. MercierdeLepinay, From trascurrent faulting to frontal subduction a seismotectonic study of Northern Caribbean plate boundary, Tectonics 11 (1992) 98–113.

[19] A.G. Bos, W. Spakman, Tectonic setting of Taiwan inferred from an analysis of GPS data, tomography and seismicity, Geophys. Res. Abstr. EGS 26th General Assembly, Nice, France, 2001.

[20] D.W. Millen, M.W. Hamburger, Seismological evidence for tearing of the Pacific plate at the northern termination of the Tonga subduction zone, Geology 26 (1998) 659–662.
[21] H. Anderson, T. Webb, New Zealand seismicity: patterns revealed by the upgraded National Seismograph Network, N.Z. J. Geol. Geophys. 37 (1994) 477–493.
[22] H. Anderson, T. Webb, J. Jackson, Focal mechanisms of large earthquake in South Island of New Zealand: Implications for the accomodation of Pacific-Australia plate motion, Geophys. J. Int. 115 (1993) 1032–1054.
[23] M.A. Moore, H.J. Anderson, C. Pearson, Seismic and geodetic constraints on plate boundary deformation across the Northern Macquarie Ridge and Southern South Island of New Zealand, Geophys. J. Int. 143 (2000) 847–880.
[24] D. Eberhart-Phillips, M. Reyners, A complex, young subduction zone imaged by three-dimensional seismic velocity, Fiordland, New Zealand, Geophys. J. Int. 146 (2001) 731–746.
[25] E.J. Hill, A deep crustal shear zone exposed in western Fiordland, New Zealand, Tectonics 14 (1995) 1172–1181.
[26] G.J.H. Oliver, An exposed coss-section of continental crust, Doubtful Sound, Fiordland, New Zealand; geophysical and geological setting, in: M.H. Salisbury, D.M. Fountain (Eds.), Exposed Cross-Sections of the Continental Crust, 1990, pp. 43–69.
[27] R.I. Walcott, Fiordland gravity models, in: M. Broadbent, F.J. Davey (Eds.), The Fiordland Seismic Refraction Survey, 1974–5, Report #124 Geophysics Division, Department of Scientific and Industrial Research, Wellington, 1978.
[28] H.J. Melosh, A. Raefsky, The dynamical origin of subduction zone topography, Geophys. J. R. Astr. Soc. 60 (1980) 333–354.
[29] R. Govers, Dynamics of Lithospheric Extension: A Modeling Study, Ph.D. Thesis, Utrecht University, Utrecht, 1993, 240 pp.
[30] R. Govers, P.T. Meijer, On the dynamics of the Juan de Fuca Plate, Earth Planet. Sci. Lett. 189 (2001) 115–131.
[31] R. Govers, M.J.R. Wortel, S.J.H. Buiter, Surface expression of slab breack-off, results from 3D numerical models, Geophys. Res. Abstr. EGS 25th General Assembly, Nice, France, 2000.
[32] J.H. Bodine, M.S. Steckler, A.B. Watts, Observation of Flexure and the Rheology of the Oceanic Lithosphere, J. Geophys. Res. 86 (1981) 3695–3707.
[33] R. Wood, G. Lamarche, R. Herzer, J. Delteil, B. Davy, Paleogene seafloor spreading in the southeast Tasman Sea, Tectonics 15 (1996) 966–975.
[34] G. Lamarche, J.Y. Collot, R.A. Wood, M. Sasson, R. Sutherland, J. Delteil, The Oligocene-Miocene Pacific-Australian plate boundary, south of New Zealand, evolution from oceanic spreading to strike-slip faulting, Earth Planet. Sci. Lett. 148 (1997) 129–139.
[35] D.L. Turcotte, G. Schubert, Geodynamics, Cambridge University Press, Cambridge, 2002, 456 pp.
[36] M. Hall-Wallace, H.J. Melosh, Buckling of pervasively faulted lithosphere, Pure Appl. Geophys. 142 (1994) 239–261.
[37] C.A. Williams, R.M. Richardson, A rheologically layered three-dimensional model of the San Andreas fault in Central and southern California, J. Geophys. Res. 96 (1991) 16597–16623.
[38] H.J. Melosh, C.A. Williams, Mechanical of graben formation in crustal rocks: a finite elemement analysis, J. Geophys. Res. 94 (1989) 13961–19973.
[39] G. Cutress, R.H. Herzer, R. Wood, J. Delteil, J.F. Lebrun, GEODYNZ Team, Fiordland Offshore Geology: Integrated Swath Mapping and Geophysics, Institute of Geological and Nuclear Sciences, Folio Series #3, 1998.
[40] W.H.F. Smith, D.T. Sandwell, Global sea floor topography from satellite altimetry and ship depth soundings, Science 277 (1956–1962) 1997, http://www.ngdc.noaa.gov/mgg/fliers/01mgg04.html.
[41] D. Nagy, The gravitational attraction of a right rectangular prism, Geophysics 31 (1966) 362–371.
[42] D. Nagy, A short program for three-dimensional gravity modeling, Acta Geod. Geophhys. Mont. Hung. 23 (1988) 449–459.
[43] P. Barnes, B.W. Davy, R. Sutherland, J. Delteil, Structure and kinematics of the offshore Fiordland margin, New Zealand, Geol. Soc. N.Z. Misc. Publ. 107A (1999) 11.
[44] D.E. Hayes, J.L. LaBrecque, Sediment isopachs: Circum-Antarctic to 30S, in: D.E. Hayes (Ed.), Marine Geological and Geophysical Atlas of the Circum-Antarctic to 30S, AGU, Washington, DC, 1991, pp. 29–33.
[45] S.S. Rao, The Finite Element Method in Engineering, 2nd edn., Pergamon Press, 1992, p. 644.