not corroborated this high value[16–18]. Quinlan and Beaumont[16] matched the stratigraphy of the Appalachian basin by using a layered visco-elastic model that had an average EET of 67 km. Although they note that a pure elastic plate model does not adequately reproduce the stratigraphy, elastic plate models in which the EET decreases with curvature would produce offlapping stratigraphic patterns as seen in the observed stratigraphy. Recently, Stewart and Watts[17] re-estimated the EET of several mountain belts by using a variable-rigidity formulation. Converting their estimates to the values of E and υ used in this paper gives a range of 50–88 km for the EET. These studies suggest that the high value found by Karner and Watts[1] is an overestimate and that a lower value averaging ~65–70 km is a better estimate. If so, our prediction of 60 km is within uncertainties.

We have established a parametrization of flexural strength at continents based on the yield stress envelope that successfully predicts the EET of the continental lithosphere at foreland basins and mountain belts. We have also demonstrated the importance of sediment fill as parameter controlling flexural strength at continents. The sediment cover is most likely to control the value of EET in places where the lithosphere's crust is thin compared with an average 35-km-thick continental crust[5], the age of the lithosphere is close to its thermal equilibrium and for which the sediment cover reaches thicknesses greater than 3–5 km. Accounting for the effect of sediments and crustal thickness should facilitate the evaluation of the flexural strength at other types of basins and continental margins. □

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Failure of plume theory to explain midplate volcanism in the southern Austral islands

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It has long been recognized that the properties of the Cook–Austral chain (Fig. 1) of volcanoes in the South Pacific are difficult to reconcile with the theory that volcanic activity in plate interiors is produced by the drift of tectonic plates over narrow, stationary plumes[1] of hot mantle material upwelling from depth. Radiometric dates[2,3] from many island samples are younger or older than would be predicted if a single plume currently located at volcanically active Macdonald seamount[4] was responsible for all of the volcanoes. Indeed, only the southernmost part of the Austral volcanic line has hitherto appeared to be consistent with plume activity, and then only within the past 6 million years (Myr)[5,6]. Here we report radiometric dates that demonstrate that these southern Austral volcanoes are actually composed of three distinct volcanic chains with a range of ages spanning 34 Myr and with inconsistent age progressions. Gravity anomalies and sea-floor fabric suggest that the volume and location of volcanism in this region is controlled by stress in the lithosphere rather than the locus of narrow plumes rising from the deep Earth.

Our data were collected during a two-month expedition to the southeastern end of the Austral chain of volcanoes (Fig. 2) aboard the RV *Maurice Ewing* in March–May 1996. Our detailed mapping reveals that, in addition to the well-known Macdonald chain, there are two other lines of volcanoes, which we have named the

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Ngatemato and Taukina chains after the ruling families of Rapa. Radiometric dating (^{40}Ar–^{39}Ar incremental heating methods) of rocks dredged from these volcanoes (Table 1) indicates that the Ngatemato chain erupted more than 30 Myr ago on lithosphere that was only 10 Myr old at the time. The volcanoes consist of low, *en échelon* ridges of slightly enriched tholeiitic basalts which differ dramatically from the radial rift zones and extremely alkaline rocks on volcanoes of the Macdonald chain. The old age of the Ngatemato chain was further confirmed by the low reflectance of the sonar signal returned to the Hydrosweep mapping system, indicating considerable burial beneath a blanket of pelagic sediment. The small Taukina chain erupted only slightly later, and is composed of small, tholeiitic, 'haystack-shaped' volcanoes frequently displaying summit calderas. It is surprising that both young (0–5 Myr) and old (29–32 Myr) dates are found for rocks dredged from the deep flanks of the Macdonald line, indicating at least two distinct periods of edifice formation. When our dated samples are reconstructed to their positions at the time of volcanism, using rotation poles[7] determined for motion of the Pacific plate with respect to fixed mantle plumes (Fig. 1), we find that there would have to be nearly as many 'plumes' as there are dated samples. The reconstructions pass through the Foundation seamounts[8], indicating a long-lived but sporadic near-ridge enhancement in melting.

Gravity data can be used to estimate the approximate volumes of young and old volcanism in the southern Austral islands by using the established correlation between the elastic strength of the oceanic lithosphere, as measured by its effective elastic thickness T_e, and the age of the oceanic lithosphere at the time of volcanism[9].

Table 1 ^{40}Ar–^{39}Ar age determinations for whole rock basalts

Sample	Name	Chain	Latitude	Longitude	Plateau		Total fusion age (Myr)
					^{39}Ar (%)	Age (Myr)	
EW96 18-1	Make	N	28° 32′ S	140° 13′ W	79	25.58 ± 1.01	27.7
EW96 13-2	Aureka	N	28° 12′ S	141° 13′ W	100	31.30 ± 0.74	31.3
EW96 13-1	Aureka	N	28° 12′ S	141° 13′ W	No plateau developed		28.8
EW96 19-1	Evelyn	T	27° 41′ S	139° 25′ W	100	25.95 ± 1.15	26.1
EW96 19-4	Evelyn	T	27° 41′ S	139° 25′ W	No plateau developed		24.2
EW96 20-6	Herema	T	27° 28′ S	140° 00′ W	100	22.47 ± 1.48	23.4
EW96 9-13	Opu	T	27° 02′ S	143° 09′ W	65	33.94 ± 0.62	39.1
EW96 9-25A	Opu	T	27° 02′ S	143° 09′ W	No plateau developed		31.7
EW96 14-1	Ra	M	28° 46′ S	141° 07′ W	88	29.21 ± 0.61	27.5
EW96 7-5	Marotiri	M	27° 57′ S	143° 36′ W	54	31.95 ± 0.82	39.6
EW96 7-7	Marotiri	M	27° 57′ S	143° 36′ W	100	3.78 ± 0.18	3.75

Ages are reported relative to biotite monitor FCT-3 (28.03 ± 0.18 Myr), which is calibrated against hornblende Mmhb-1 (523.5 Myr). Plateau ages are the mean of concordant step ages (3 or 4 steps for each sample that developed a plateau), weighted by the inverse of their variances. Calculations use the following decay and reactor interference constants: $\lambda_\kappa = 0.581 \times 10^{-10}\ yr^{-1}$; $\lambda_\beta = 4.963 \times 10^{-10}\ yr^{-1}$; $(^{36}Ar/^{37}Ar)_{Ca} = 0.000264$; $(^{39}Ar/^{37}Ar)_{Ca} = 0.000673$; $(^{40}Ar/^{39}Ar)_{Ca} = 0.01$. The volcanic chain to which each seamount belongs is identified by M, N or T for the Macdonald, Ngatemato and Taukina chains, respectively.

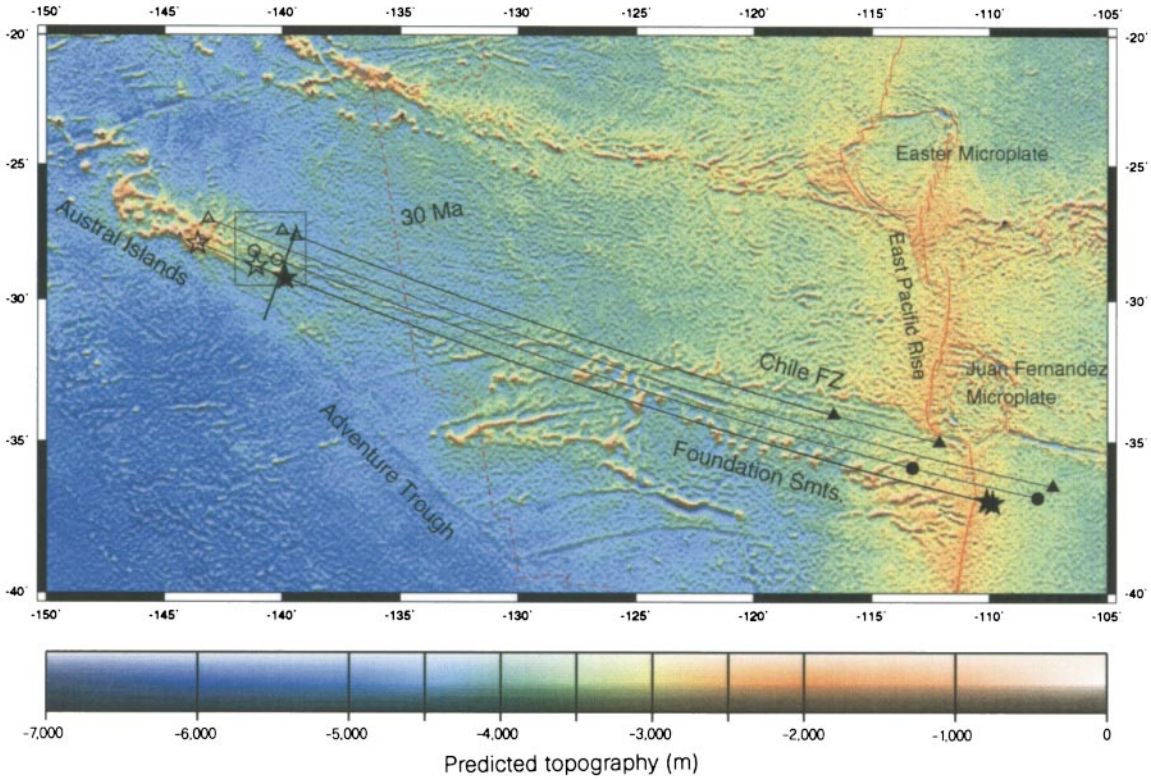

Figure 1 Bathymetric map of the South Pacific seen from ship soundings and satellite altimetry[24]. The solid red line is the locus of present-day sea-floor spreading in the Pacific. The broken red line is the 30-Myr isochron[25]. The box shows the location of the region surveyed in the southern Austral islands. Open circles (Ngatemato), triangles (Taukina) and stars (Macdonald) indicate the location of dredge sites for dated volcanic rocks; filled counterparts show the reconstructed positions of the dated volcanic rocks when they erupted using Pacific-hotspot finite rotation poles[7]. The thick black line gives the location of the profile shown in Fig. 3.

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We begin at 30 Myr by Ngatemato volcanic load 4.5 km high erupting, approximately as a gaussian function (Fig. 3a), on a young, hot, weak plate ($T_e = 5$ km). This load causes a moat 3.3 km deep to form, such that the net height of the volcano is only 1.2 km (Fig. 3b). The Macdonald volcanism then erupts a small, volcanic load 1 km high 30 Myr later (Fig. 3c) on an older, stiffer ($T_e = 15$ km) plate. The moat it creates is 630 m deep (Fig. 3d), but because the volcano rests on the flanks of the larger, older volcano, the net height after plate bending is still 800 m. The older Ngatemato volcano is also affected by this younger volcanism, and becomes even further submerged in the moat created by the younger load, thus reducing its apparent height by another few hundred metres. The net effect of this simple modelling exercise is a bimodal seamount chain (Fig. 3d) with the Macdonald volcano

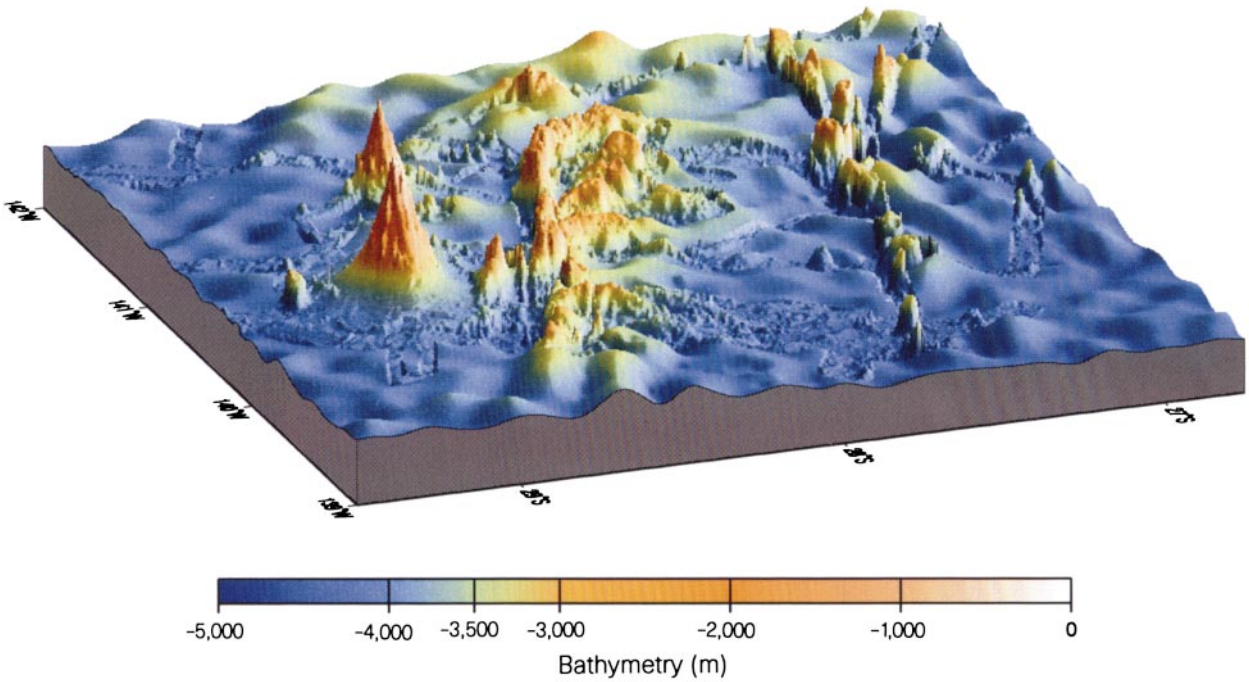

Figure 2 Perspective view of the southern Austral islands showing the three distinct lines of volcanoes. High-resolution swath bathymetry has been overlaid on a base map of bathymetry predicted from satellite altimetry[24], as there were too few ship soundings in this area before our expedition to determine even the grossest contours. The view is from the southeast, with illumination from the north. The Ngatemato seamounts (centre) are low, *en échelon* ridges with summit calderas, whereas the Taukina seamounts (right) are individual cones; both have a convex shape. In contrast, the Macdonald seamounts (left) display prominent rifts and more concave slopes.

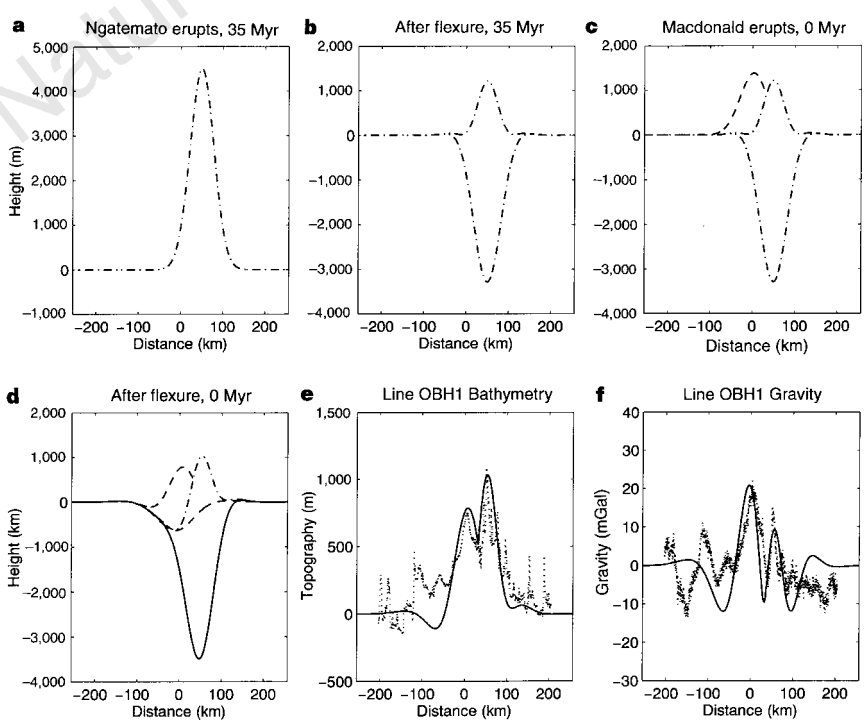

Figure 3 Flexural modelling of lithospheric loading at two distinct times. **a**, Load from Ngatemato volcanism. **b**, Ngatemato load subsided after lithospheric flexure. **c**, Load from Macdonald volcanism (dashed line) added to flank of Ngatemato load. **d**, After lithospheric flexure from Macdonald load (dashed line). Solid line is the combined moat from both loads. **e**, Net predicted topography (solid line) compared to observed topography (dots) along line OBH1 in Fig. 1. **f**, Net predicted gravity anomaly (solid line) obtained from the density effects of the topography in (solid line in **e**) and the depression of the crust–mantle boundary predicted from the plate bending in (solid line in **d**) compared with the observed gravity anomaly (dots).

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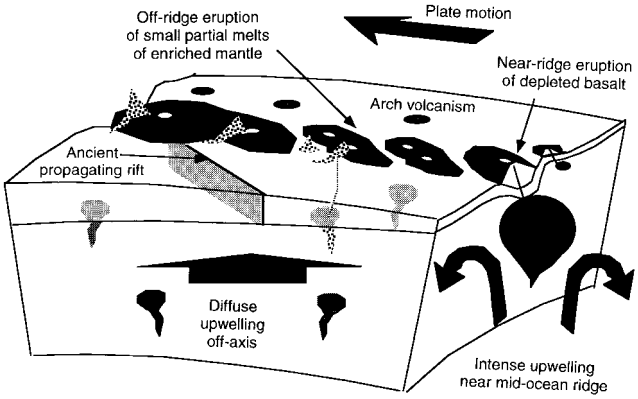

Figure 4 Schematic representation of a model for volcanism in the Austral islands. We assume that the upper mantle beneath French Polynesia is enriched in several different easily melted components that have been reinjected into the upper mantle by earlier subduction of oceanic crust, continental crust, and sediments. Their unusual isotopic signature would be homogenized and diluted by the large degrees of partial melting that occur near the mid-ocean ridge but preserved in the smaller off-ridge seamounts. These more exotic melts are pervasively available beneath the plate on account of diffuse upwelling, but are preferentially channelled to the surface by pre-existing cracks in the plate, topography on the base of the plate, and older volcanic conduits.

smaller than the Ngatemato volcano, and a net gravity anomaly (the difference between the mass excess of the volcanoes and the mass deficit caused by their combined flexural signals) that is larger over the Macdonald chain (Fig. 3e), owing to the asymmetrical crustal flexure across the section.

Other profiles measured confirm that most of the Macdonald chain is young (0–5 Myr) and most of the Ngatemato chain is old (~30 Myr). The effective elastic thickness of the plate supporting Marotiri to the northwest is only 10 km, as opposed to the expected 15 km if the entire feature were only 5 Myr old, suggesting that there is more mixing of volcanic ages in the northern section of the Macdonald chain of volcanoes. We believe that this complicated interaction of the flexural effects of volcanoes of different ages is responsible for the anomalously low effective elastic plate thicknesses reported for the South Pacific[10–12]. Young volcanoes are not loading an old, anomalously weak plate; rather, the majority of the load erupted when the plate was young.

The flexure models suggest a causal mechanism for the spatial association of these three chains spanning a 34 Myr age range. The Taukina chain lies along the flexural arch of the plate bending produced by the Ngatemato chain. Arch volcanism is well documented in Hawaii, and presumably indicates that either the extensional stress in the upper elastic plate facilitates and focuses magma outpouring, and/or that the arch provides a structural trap[13] for low-density magma (Fig. 4). The Macdonald chain also erupts where the lithosphere is in tension from Ngatemato loading, although somewhat inboard of the arch maximum. The volume of all three chains is also modulated along strike (Fig. 4), with maximum volumes corresponding to the intersection of the north-northwestern line with the Adventure trough, an ancient propagating rift[14].

Other morphological evidence from the southern Austral islands also suggests a wide range of ages for volcanism, which is inconsistent with plume theory. Deeply submerged, flat-topped seamounts[15] are interspersed with young volcanoes, suggesting erosion at wave base during a much earlier phase of volcanic activity when the sea floor was shallower. Furthermore, individual islands within the long chain display totally different isotopic signatures, thought to be characteristic of different mantle source regions[16], making the hypothesis of a single plume even more unlikely. Modifications to plume theory that might explain the Cook–Austral chain include proposals such as fortuitous alignment of several distinct plumes[17] or volcanic rejuvenation that repaves older features with a veneer of young rock long after it has passed over the plume[18]. Our data suggest that such minor adjustments to plume theory are inadequate.

The picture that emerges instead has the eruption of the Ngatemato chain as the primary event, beginning more than 30 Myr ago by excess melt production near a mid-ocean ridge. The locus of later volcanism was controlled by stresses in the lithosphere caused by Ngatemato loading and modulated by another ancient plate structure, the Adventure trough. Seismic tomographic imaging of the upper mantle of the South Pacific[19] and dynamic modelling[20] demonstrate that the upper mantle beneath this entire region is anomalously hot and weak, suggesting there were unusual amounts of partial melt and broad-scale upwelling. The geochemistry of the mantle melts is more consistent with sampling an upper mantle enriched with easily melted components through plate subduction than with transport of primitive mantle from deeper regions that never participated in the plate tectonic cycle[21–23]. The plate structures merely organize the outflow of this easily melted component entrained in the diffuse upwelling into the chains we observe today. Shearing between the drifting plate and the underlying melt source would lead to extremely short age progressions of volcanoes tapping an individual melt pocket. Although we cannot definitively rule out the existence of a plume beneath the Macdonald seamount, if one exists in this region it is responsible for only a small amount of the very substantial volume of off-ridge volcanism. □

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