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Deep crustal structure of the Tuamotu plateau and Tahiti (French Polynesia) based on seismic refraction data

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Abstract:

In French Polynesia, the young (<5Ma) Society Islands appear to result from intraplate volcanism, while the old (>50 Ma) Tuamotu plateau was likely created at or near the ridge axis. The structure of the crust between those two archipelagoes is constrained by a 300 km long refraction seismic profile. Crustal and upper mantle arrivals recorded by 6 OBHs and 3 land stations were used to provide a 2D model of the crust. Results of our study, combined with that of Grevemeyer et al. [2001] show a slight flexure below the Tahiti apron, while a deep crustal root (21 km) underlies the Tuamotu plateau. These structures reflect the different modes of load emplacement and compensation mechanisms between these two volcanic edifices, consistent with an increasing elastic thickness of the oceanic lithosphere with age.

Introduction

French Polynesia in the South Pacific is a region with a great concentration of volcanic islands and seamounts as well as oceanic plateaus. This, together with an abundance of active hotspots has caused some to suggest the presence of a "superswell" [McNutt et al., 1990]. Interestingly, the elastic thicknesses calculated from volcanic edifices in French Polynesia do not fit the general decaying exponential relation (as a function of increasing age) established from most other volcanic islands [Goodwillie & Watts, 1993]. The reasons for this misfit are not understood and have prompted some to suggest the lithosphere is thermally reset at the time of hotspot volcanism [Calmant & Cazenave, 1986]. Other researchers have suggested the presence of buoyant underplated roots of mafic material may contribute to support some of the surface load [Wolfe et al., 1994; Caress et al., 1995].

In 1989 a marine seismic survey (MidPlate II) was conducted aboard the German vessel R/V SONNE in French Polynesia to constrain the deep crustal structure of the Society and Tuamotu archipelagoes and address questions concerning the mode of isostatic compensation, the degree of flexure of the lithosphere and the thickness and composition of the underlying oceanic crust. These two island chains display marked differences in morphology and age with respect to the adjacent oceanic crust. The Society islands are a young intraplate hotspot chain with ages ranging from 0-5 m.y. overlying 65-90 m.y. old oceanic lithosphere [Munschy et al., 1996]. The Tuamotu Plateau is known from dredge samples and sediment ages from a DSDP drill hole to be at least 50 m.y. old [Schlanger, 1984] and thus close to the age of the adjacent 50-65 m.y. old oceanic crust, which suggests a near axis origin.

We present the results of a NNE-SSW seismic refraction profile between the Tuamotu Plateau and the Society chain recorded by ocean bottom hydrophones (OBH) as well as landstations. These data complement previous refraction seismic study of Talandier & Okal, [1987] who used land stations and shots at sea, and assumed that layering was everywhere horizontal in the absence of reverse profiling. The velocity model obtained from modeling of the refraction data is discussed with regard to the deep structure of the islands edifices and the compensation mechanisms of the adjacent lithosphere.

Geological background

The study area is situated in the south of the Pacific Ocean in the so-called "Pacific Super Swell" zone [McNutt, 1998].

This zone is characterized by anomalously shallow sea-floor and by numerous volcanic islands and seamounts aligned along approximately NW-SE linear trends. The oceanic crust separating the Society and Tuamotu archipelagoes, aged between 58 and 70 Ma, shows structural features (transform faults or magnetic lineations) oblique to the islands trails [Mayes et al., 1990; Munschy et al. 1996] (Figure 1).

The Society islands show a westward increase in age from the islands of Meetia-Teahitia, were volcanism is active [Talandier and Okal, 1987; Cheminee et al., 1989; Hekinian et al., 1991], to the island of Maupiti, at the northwestern edge of the Society trail, dated at about 4.3 Ma [Duncan and McDougall, 1976; White and Duncan, 1996].

The Tuamotu Archipelago is older though its age is less well constrained, the volcanic basement being totally covered by a thick limestone cap. The only volcanic samples were dredged on the northwestern end of the plateau and provided Ar/Ar dates of 41.8 ± 0.9 Ma [Schlanger et al., 1984]. Sediments at its northwestern edge give maximum age of 40-55 Ma [Burckle and Saito, 1966; Martini, 1976; Le Suave et al., 1989]. Those dates give only a minimum for the formation age of the Tuamotu plateau which could be as old as 70 Ma [Okal and Cazenave, 1985, Gordon and Henderson, 1987, Talandier and Okal, 1987; Gutscher et al., 1999], an age very close to that of the underlying 30-70 Ma oceanic crust [Mayes et al., 1990; Munschy et al., 1996].

The Tuamotu and Society archipelago present two different morphologies that give two different signatures on both bathymetric and gravimetric data. The Tuamotu Archipelago is composed entirely of atolls and underwater aprons located above a broad plateau whose bathymetry does not exceed 2000m. No comparable plateau surrounds the Society Archipelago, which consists of atolls and islands rising above a 4000m deep seafloor.

The gravimetric anomaly, consequently, is very different (Figure 2a). The Society Islands are marked by a strong (up to 120 mGal) but short wavelength positive anomaly. In the Tuamotu, the gravimetric anomaly is broad. It shows a moderate positive maximum (typically < 70 mGal) below the main atolls and negative values surrounding the plateau.

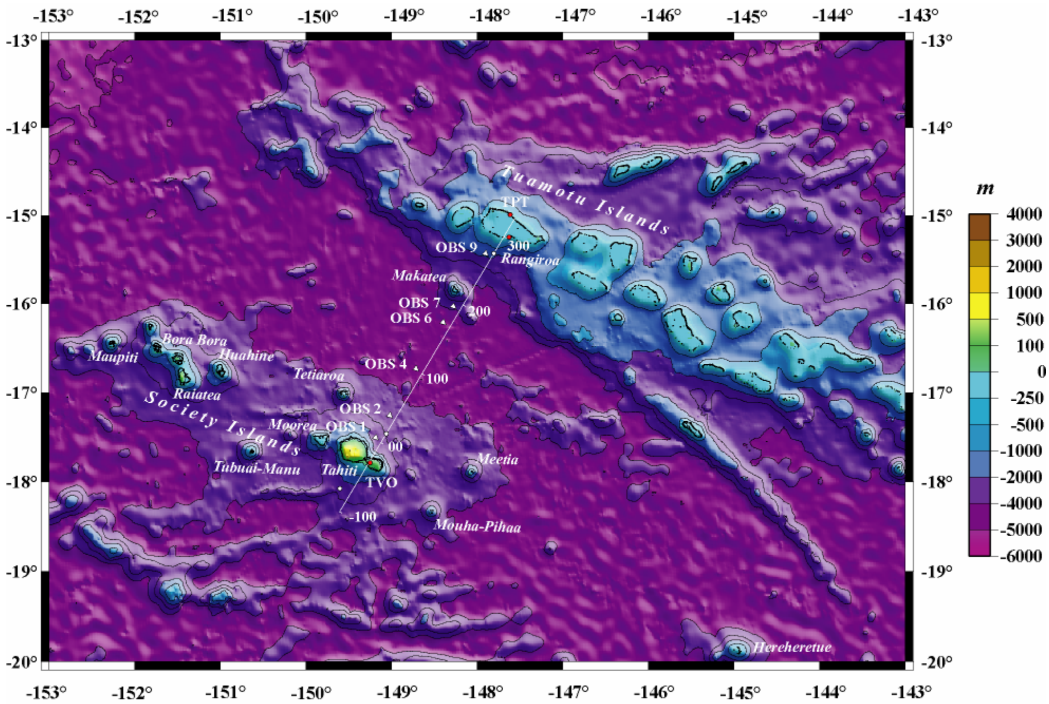

Figure 1: Bathymetry of the French Polynesia and location of seismic refraction profile, OBHs, land stations and dynamite shots (see text for details). White circles are locations of the three explosions used in this study. Red circles are locations of land-stations.

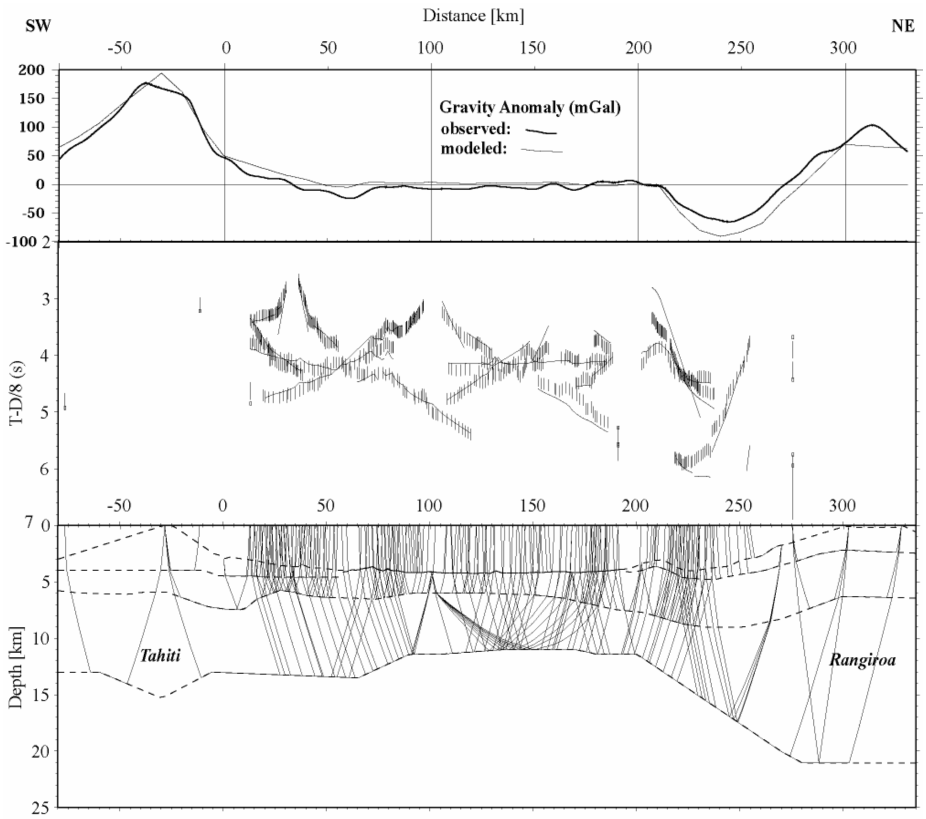

Figure 2: a) Free-air gravity anomaly observed and modeled. See text for explanations. b) Travel-time data obtained from OBH record sections and land stations record, plotted as travel-time versus the shot location related to position of OBH 1 (northeast positive, southwest negative). Reduction velocity is 8 km/s. c) Ray paths used to model the isovelocity structure along the profile.

Seismic data

During the Midplate II survey, data were collected along two directions, parallel and perpendicular to the islands trails. The Institute of Geophysics of the University of Hamburg (IGH) did the data processing and interpretation of the profiles parallel to the Society trail [Grevemeyer et al., 2001]. We present here the results of profile 1, a seismic refraction profile between the Society and Tuamotu Archipelagoes (Figure 1).
The source consisted of 6*16 liter airgun array providing a total volume of 96 litres. The average shot spacing was 250-300 m. During the survey, additionally to the airgun shots, dynamite charges were detonated to provide a source with deeper penetration.
9 ocean bottom hydrophones (OBH) were deployed, 6 of these OBHs provided good quality data.
The processing included band pass filtering (5-20 Hz), relocation of source and OBHs, identification and hand picking of the phase arrivals (Figure 3).

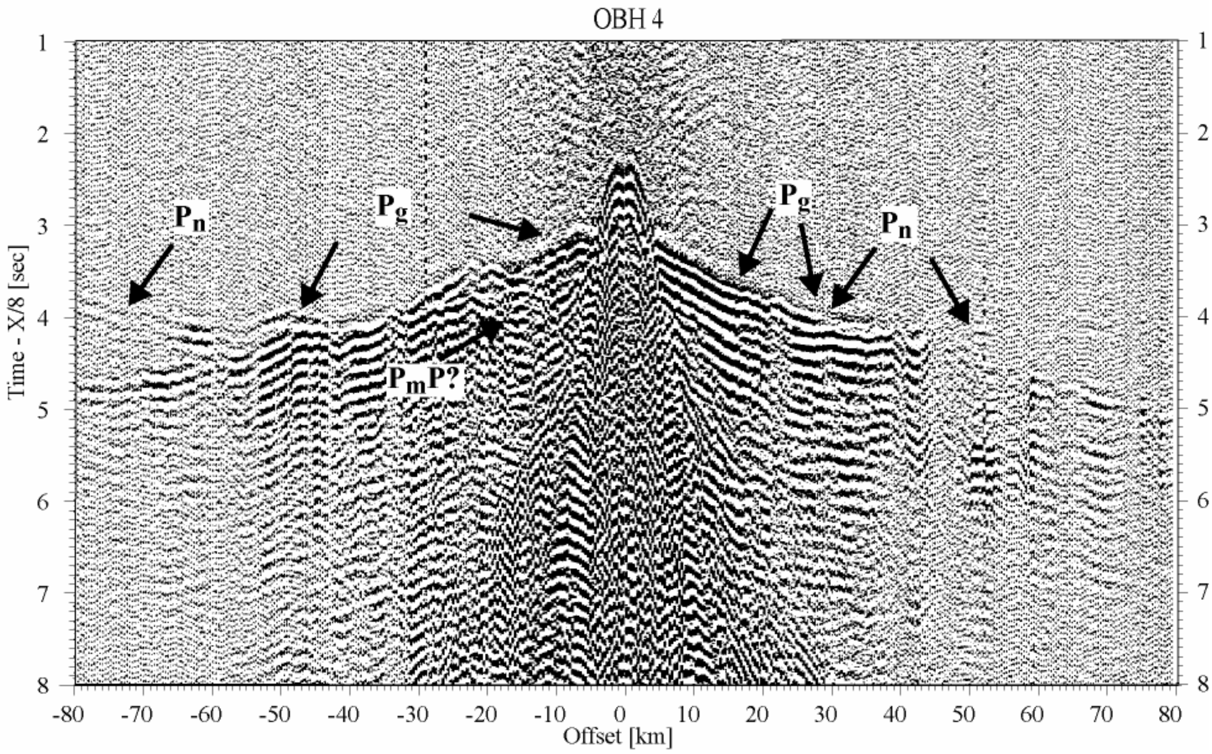

Figure 3: Seismic refraction record section of ocean-bottom seismometers 4 (OBH4). Arrows point to turning rays from the upper mantle (Pn), refracted rays from the intra crustal boundary between basalts (layer 2) and gabbros (layer 3)(Pg), and reflection on the Moho (PmP). Reduction velocity is 8 km/s.

Additionally, records on the onshore stations of the Reseau Sismique Polynesien (RSP) were provided by the Laboratoire de Geophysique (LDG) of the French Commissariat à l'Energie Atomique (CEA). We used the arrivals of 3 dynamite shots recorded by 3 stations, TVO (Tahiti), VAH (Rangiroa) and TPT (Rangiroa), located on or immediately adjacent to the profile 1 (Figure 1. These long-distance arrivals are very useful as they present the records with the greatest offsets.
Starting from the assumption of a simple layered crust [White et al., 1992; Mutter & Mutter, 1993] (a volcanosedimentary layer, a basaltic layer and a gabbroic layer), we identified 3 main phases plus the water-path direct arrival: - Turning rays from the upper mantle (Pn), - refracted rays from the intra crustal boundary between basalts (layer 2) and gabbros (layer 3), (Pg), - and a reflection off the Moho (PmP). Additional intermediate reflections and refractions on the volcanosedimentary/basalt or basalt/gabbro boundaries were often observed and picked. The quality of records was very variable from one OBH to another (Figure 3).
Once the different phases were identified, we used the ray-tracing software RAYINVR [Zelt and Smith, 1992], to model the different arrivals. We tried to adjust the fit using variations in layer thicknesses

rather than lateral velocity gradients (Figure 2b). The final model is a 3 layer crust overlying the upper mantle (Figure 2c & 4).
The seismic data along profile 1 alone do not provide sufficient constraints on the velocity structure immediately below Tahiti Island. In particular, the depth of the crust/mantle boundary here is not constrained. Consequently, below Tahiti, we used the crust/mantle boundary provided by Midplate II profiles 2 and 3 modeled by Grevemeyer et al. [2001] to model gravity and to calculate the isostatic columns.

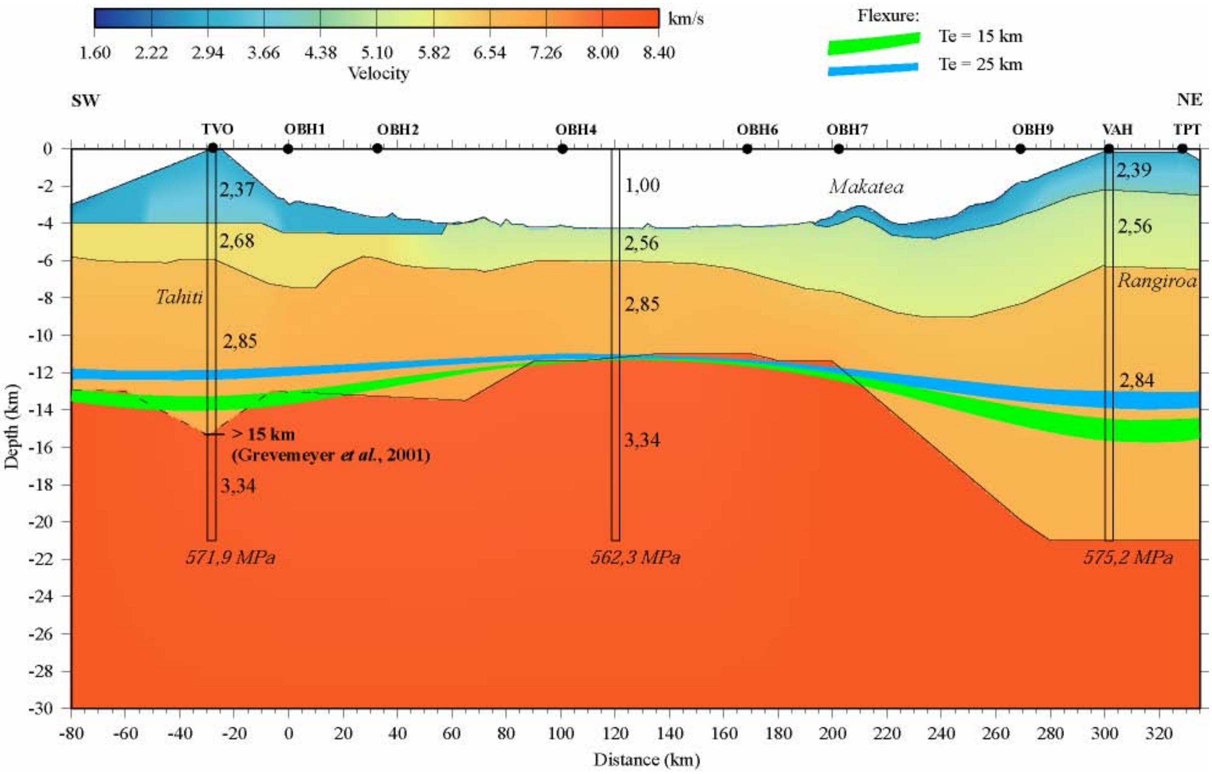

Figure 4: Isovelocity model. Contour line each 0.5 km/s. Note that the crust/mantle boundary below Tahiti is drawn after Grevemeyer et al. [2001]. We calculated the total load of three isostatic columns whose densities are indicated, and the elastic flexure assimilating sea-bottom topography to the load geometry for an effective elastic plate of thickness (Te) of 25 and 15 km (see text for explanation).

Discussion and conclusions

Crustal structure and Moho depth below the Tuamotu

The major contribution of profile 1 is the information provided regarding the Moho geometry below Rangiroa. Four receivers, OBH 7 and 9, and VAH and TPT stations, provide information about the crustal structure below the atoll. Following the assumption of a three layers crust, the best fitting model is that with Moho at 21 km. In this model the basaltic layer 2 is thinner than its average value, while the volcanosedimentary layer is thickened by the cap of limestone characterizing the atolls.
Talandier and Okal [1987], on the basis of waves dispersion and refraction seismic interpreted within the framework of a homogeneous three-layers over a half-space model, proposed a much deeper Moho (~31 km). Our study confirms a thicker than normal crust, but not as deep as 31 km. Moreover, the 1mn satellite free-air gravity data [Sandwell and Smith, 1997] present a 100 mGal maximum, centered above Rangiroa and Tuamotu atolls in general, which agree better with a shallower crust/mantle boundary. Our own velocity model, that we converted in a density model, following Ludwig et al. [1970], presents a good fit to the observed free-air gravity (Figure 2a). Our model reproduces the average values and spatial variations of the observed gravity anomaly. The only important deviation concerns the value of the maximum positive anomaly centered above the atoll. Our density model fails to reproduce the observed 100 mGal anomaly, only reaching 78 mGal. With a

deeper crust/mantle boundary, as proposed by Talandier and Okal, the calculated gravity anomaly would be even lower and the misfit would increase.
Though our velocity model gives a 10 km shallower Moho below the Tuamotu than the model of Talandier and Okal [1987], our conclusions are similar. The crustal root below the Tuamotu plateau offers a simple explanation for the low value of the gravity anomaly. As noted by Talandier and Okal [1987], the geoid variations of the Tuamotu plateau is low when compared to that observed around the Society islands or other intra-oceanic volcanic islands [see Watts and Ten Brink, 1989, for example].

Crustal structure around Tahiti

Around Tahiti, our modeling of the refraction data shows that the thickened crust is not limited to the localized root, but extends well beyond the bathymetric expression of the island, up to 100-130 km northward away from the center of the island. In this area, between obh02 and obh04, the refraction seismic modelling images a deep (~ 13km) crust/mantle boundary. Further south, towards Tahiti, below the island and on its other flank, this boundary is not sampled by seismic data, but gravity data suggest this limit remains at least at this depth (Figure 4).
Free-air gravity data along profile 1 are compatible with the 15 km crustal root proposed by Grevemeyer et al., [2001] below Tahiti apron.

Compensation mechanisms - Evolution with time

The Society and Tuamotu Archipelagoes present two very different crustal structures, corresponding to two different scales of crustal thickening and isostatic response to topography.
We calculated the isostatic columns for three vertical columns using the geometry and density values derived from our velocity model. Results (Figure 4) show the region is close to isostatic equilibrium. By calculating the 3-D topography of the sea-floor above a reference bathymetry as a load on the lithosphere, we also calculated the resulting flexure using a simple elastic model (Figure 4). The elastic thickness was alternatively fixed to 25 km (following Grevemeyer et al. [2001], blue curve) and 15 km (green curve). The reference bathymetry used to define the load geometry, was arbitrary chosen to be equal to that of the central portion of the section, in-between Tuamotu and Society. The thickness of the two curves reflects the two end-member values (2,8/2,4 and 2,4/2,35) used for the load and infill material density in the flexure model.
The crustal structure below Tuamotu is characteristic of a plateau whose topography is isostatically compensated by a broad crustal root. The bathymetric expression of the plateau corresponds with that of the thickened lower crust as testified by the bathymetric and gravimetric maps as well as by the crustal profile we present. This situation corresponds to local isostatic compensation of a wavelength much shorter than that tested in the flexure model.
The much more localized topography of Tahiti is associated to a flexural deepening of the Moho testified by the crustal profiles presented by Grevemeyer et al. [2001]. This situation corresponds to a mode of regional isostatic compensation, with a longer flexural wavelength, compatible with those observed in the flexure model. The difference between those two structures could be due to differences in the thermal state of the oceanic crust at the time of volcanism. The Tuamotu Plateau is an old (> 45 Ma) edifice whose history began at or near the spreading center. The young Society Islands (< 5Ma), on the other hand, result from intra-plate volcanism occurring on an already cool and strong oceanic crust. Consequently those two regions presented, at the time of volcanism, two different crustal elastic thicknesses and, therefore, responded differently to loading. The Tuamotu Plateau presents a thickened layer three and could be near isostatic equilibrium since it was emplaced [Sandwell and McKenzie, 1989; Mutter and Mutter, 1993]. On the other hand the Society islands aprons are emplaced on and thus supported by a strong lithosphere [Watts and Ten Brink, 1989].

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