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Geodynamic modeling of the South Pacific superswell

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ABSTRACT

The South Pacific superswell is a broad region situated in the south central Pacific, characterized by numerous geophysical anomalies including very shallow seafloor compared to the depth predicted for its age by classical seafloor subsidence models, a negative geoid anomaly, a mantle characterized by slow seismic velocities, and a high volcanism concentration. Until recently, the image of the mantle provided by the seismic tomography models was rather blurry due to the sparse distribution of seismometers. This shortcoming has been lately overcome by regional seismic observations on islands and seafloor. The new P-wave seismic tomography model derived from these regional data in addition to global data provides a more reliable and precise image of the mantle, in particular beneath the French Polynesia region. We use it to perform numerical simulations of the instantaneous flow occurring in the mantle, using realistic laws for converting velocity anomalies into density anomalies and for describing the viscosity variations. We compute the associated dynamic topography and geoid anomaly. We show that the superswell could be caused by the large-scale slow velocity anomalies in the lower mantle, which are recognized as the South Pacific superplume. The surface geodetic observations are explained by a model including a low viscosity asthenosphere situated immediately beneath the lithosphere, and a lower mantle viscosity 100 times greater than the upper mantle one. Our study assumes a purely thermal origin of the velocities anomalies. Although the existence of compositional heterogeneities is often invoked to explain the dynamics of the South Pacific superplume in previous numerical and laboratory experiments, and are important to account for plume/superplumes phenomenology, we cannot definitively conclude the presence of such compositional heterogeneities from our geodynamic modeling.

1. The South Pacific superswell

1.1. Volcanism

Situated in the central south Pacific, the south Pacific superswell is a region characterized by numerous geophysical anomalies. In particular the superswell is associated with a great concentration of volcanism. In terms of volcanism rate, 14% of the active volcanism is concentrated in an area covering less than 5% of the globe (Sleep, 1990). There are several active volcanoes (red disks in Fig. 1a). A wide range of volcanic features should be noted: en echelon ridges, chains of mid-plate volcanoes and isolated seamounts. The ocean island basalts from the volcanism in the superswell area are geochemically unique since they exhibit wide variation in isotopic and trace element compositions (e.g., Vidal et al., 1984; Bonneville et al., 2006), suggesting geochemical heterogeneities in the mantle beneath the superswell. The five main chains in the region are the Society, the Marquesas, the Tuamotu, Pitcairn-Gambier and the Cook-Austral (Fig. 1a). Their characteristics often depart from the classical definition of a hotspot chain, which accounts for the simple interaction of a mantle upwelling with the overriding lithosphere. The age progression in the volcanic chains is often short and the orientation of the chains does not systematically correspond to the motion of the oceanic plate, like in the Marquesas. The lithosphere seems to exert a considerable influence on the location of the volcanism, like in the Austral Islands where two periods of linear volcanism, separated by 10 m.y., are superimposed on the same volcanic edifices (Bonneville et al., 2006). The morphology of the depth anomalies associated with the hotspot chains (hotspot swell of several hundred kilometers in wavelength) also indicates a complex history for the chain formation (Adam et al., 2005). However, a recent study shows that mantle convection in the shallow part of the mantle (depths 0–240 km) is responsible for the volcanism emplacement and for the swells' morphology (Adam et al., 2010).

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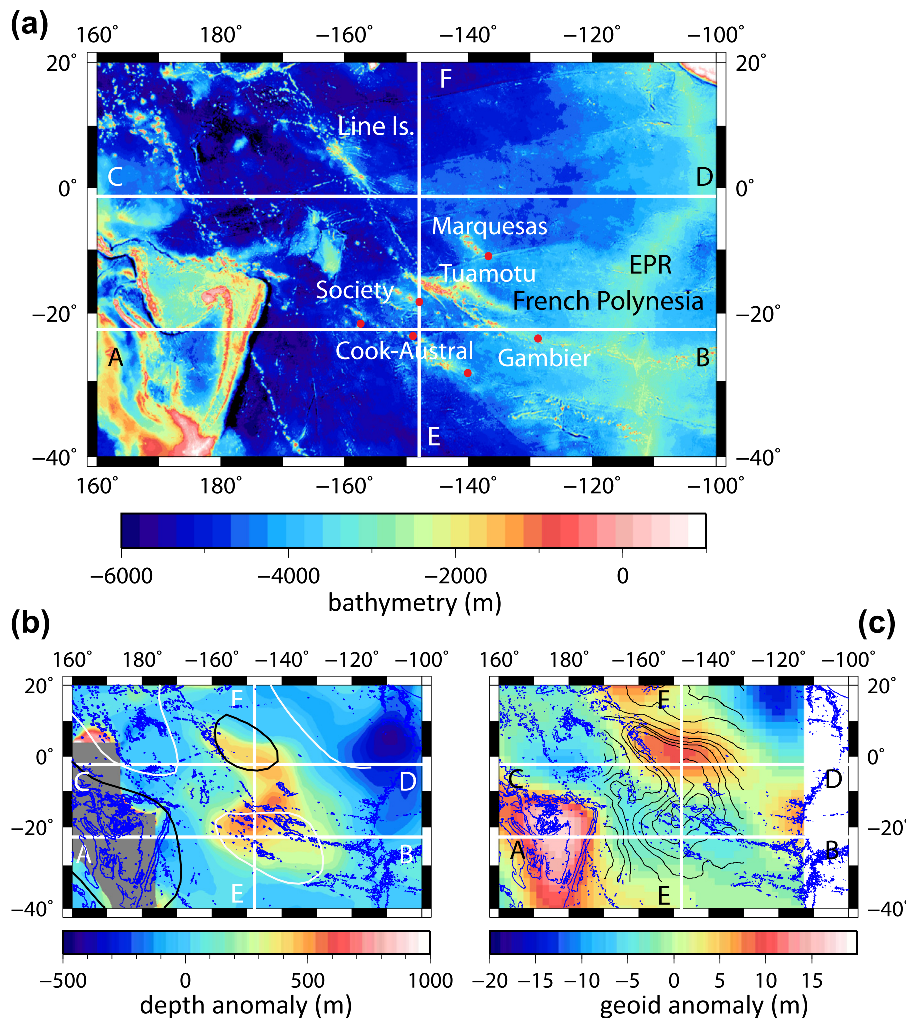

Fig. 1. Bathymetry of the Pacific in the superswell area and main anomalies associated with this area. (a) Bathymetry and emplacement of the profiles along which the mantle structure is discussed. The red disks represent recent volcanism. (b) depth anomaly from Adam and Bonneville (2005) through the MiFil filter; (c) geoid anomaly from Cadio et al. (2011), who applied a wavelet method to analyze the GRACE gravity data. The black and white thick lines in panel b are respectively the iscocontours of the +10 and −5 m of the geoid anomaly characterized by Cadio et al. (2011). The black lines in panel c are the isocontours of the depth anomaly from Adam and Bonneville (2005), displayed every 100 m between 0 and 600 m. The blue lines are the 6000, 3000 and 0 m isobaths from Smith and Sandwell (1997). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

1.2. Depth anomaly

The term "superswell" itself comes from the fact that the seafloor in French Polynesia is unusually shallow compared to other seafloor of the same age. Indeed, this region subsides less rapidly away from the East Pacific Rise than any thermal subsidence model of the oceanic lithosphere predicts (McNutt and Fischer, 1987). Several studies try to assess the bathymetric elevation (Van Wykhouse, 1973; Mammerickx and Herron, 1980; Cochran, 1986; McNutt and Fischer, 1987; McNutt et al., 1996; Sichoix et al., 1998), but the description of the location and extent of the superswell remained approximate for a while. One talked indeed about "a region in the South Pacific, to the west of Easter Island" (Mammerickx and Herron, 1980) or about "a broad area of French Polynesia" (McNutt, 1998). The design of filtering methods, especially adapted for bathymetry (Hillier and Watts, 2004; Adam et al., 2005) allowed a precise quantification of the depth anomaly associated with the South Pacific superswell. We will use here the characterization found through the MiFil method (Adam et al., 2005; Adam and Bonneville, 2005). This method consists in determining the depth anomaly and then filtering it through two stages: a first one to roughly remove the volcano component by minimizing the depth anomaly and a second one to smooth the shape and totally remove the small spatial length scale remaining topography using a median filter. The most adequate radii for the characterization of the depth anomaly associated with the South Pacific Superswell are 50 km for the minimizing filter and 700 km for the median filter (Adam and Bonneville, 2005). The depth anomaly is the difference between the observed depth and a theoretical depth provided by thermal subsidence models which describe the evolution of the seafloor depth with its age. In Fig. 1b, we show the depth anomaly obtained from the GDH1 thermal subsidence model (Stein and Stein, 1992). The superswell extends between latitudes 10 °N and 30 °S and longitudes 130 °W and 160 °W and has a maximal amplitude of 700 m, on a seafloor displaying ages between 30 and 115 Ma. It is not a simple swell, but a hemispheric shaped feature, of an approximate wavelength of 3000 km, composed of two branches (Fig. 1b). The southern branch corresponds to the location of French Polynesia. The northern branch, described by Adam and Bonneville (2005), is not clearly correlated with volcanic features. The only volcanic chain over this area is the Line Islands, which is a fossil alignment displaying ages between 35.5 and 93.4 Ma (Schlanger et al., 1984). These characteristics remain similar when other thermal subsidence models are used, although the amplitude of the swell varies. It reaches 800 m when the PSM (Parsons and Sclater, 1977) model is used for example.