Fossil Hotspot-Ridge Interaction in the Musicians Seamount Province: Geophysical Investigations of Hotspot Volcanism at Volcanic Elongated Ridges

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Abstract

The Musicians Seamount Province is a group of elongate volcanic ridges and single seamounts located north of the Hawaiian Chain. A 327° trending chain of seamounts defines the western part of the seamount province and has been interpreted as the expression of a Cretaceous hotspot beneath the young and northward moving Pacific Plate. To the east, elongated E-W striking ridges dominate the morphology. Similar volcanic elongated ridges (VERs) around the world have been identified from satellite altimetry measurements. Many of these VERs are obviously related to hotspot-ridge interaction, but a number of open questions regarding their structure and origin remain. In 1999, two 400 km long VERs of the Musician seamount group were studied in detail during cruise SO142 of the RV SONNE. Wide-angle seismic data were gathered along four profiles crossing two prominent ridges. In total, 45 OBH (Ocean Bottom Hydrophones) were deployed with a mean spacing of 4 km. We present tomographic images of the volcanic edifices with the aim of identifying the style of volcanism produced by plume-ridge interactions. Our studies of the Musicians VERs indicate that crustal thickening occurs in oceanic layer 2 rather than in layer 3. This extrusive style of volcanism appears to strongly contrast with the formation processes of aseismic ridges, where crustal thickening is mostly accommodated by intrusive underplating of high-velocity lower crust. In addition to the seismic data, high-resolution bathymetry was acquired which yields a detailed image of the morphology of the VERs. From the occurrence of flat-top guyots in the study area and from the unique geomorphologic setting, two independent age constraints for the Pacific crust during the Cretaceous 'quiet' zone are obtained, which allow to present a tectonic reconstruction for the formation of the Musicians VERs that also explains the absence of volcanic edifices north of the Pioneer fracture zone and the re-initiation of volcanism south of the Murray fracture zone. Hotspot-ridge interaction leads to a channeling of melt from the plume to the nearby spreading center over a maximum distance of 400 km. The Musicians VERs were formed by mainly extrusive volcanism on top of this melt channel as the spreading center gradually moved southeastward away from the hotspot, resulting in the observed increasing length of the individual volcanic ridges to the south. The proposed formation model may be applicable to a number of observed volcanic ridges in the Pacific, including the Tuamotu Isles, the eastern portion of the Foundation chain, and the western termination of the Salas y Gomez seamount chain.

1. Introduction

A great variety of volcanic structures can be observed on the oceanic seafloor. A large fraction of this volcanism has evolved near oceanic spreading centers and different models of hotspot-ridge interaction have been proposed to explain its origin related to this observation. V-shaped ridges or seamount chains, most pronounced at the Reykjanes Ridge south of Iceland or the SE Indian Ridge, are understood to be produced by fixed or moving melt anomalies on a rise axis [Vogt, 1971; Johnson and Vogt, 1973] or the propagation of rift segments [Hey and Vogt, 1977; Sempere et al, 1996]. Broad continuous ridges are often observed where a major plume is centered on a spreading axis. The thickened crust produced by enhanced plume melting leaves trails on the spreading crust like Cocos/Carnegie Ridge [Lonsdale and Klitgord, 1978] or Ninetyeast Ridge [Mahoney et al., 1983]. An additional model for the development of aseismic ridges has been proposed by Morgan [1978], who postulated a sub-lithospheric melt flow from an off-axis hotspot to a spreading center. The additional melt supply increases the volcanic production where the channel reaches the ridge axis and causes the formation of volcanic ridges in the order of 2 km height, which display a distinct azimuth resulting from the sum of the absolute and relative plate motions. The significant new aspect of this idea was that here, the plume and spreading center interact over a distance of up to several hundred kilometers. Isotope geochemical evidence for far-distance interaction between plumes and ridges was subsequently found by a number of studies e.g. Verma and Schilling [1982], Hanan et al [1986], Douglass et al. [1995], [*Yu et al.,* 1997; *Kingsley and Schilling,* 1998]. However, the azimuths of many aseismic ridges in the Atlantic as well as in the Pacific differ significantly from those predicted by the Morgan [1978] model. Aseismic ridges between Clipperton and Galapagos FZ, so-called 'cross-grain ridges' are interpreted to be produced by the filling of tensional cracks in the lithosphere that are caused by the drag of mantle convective rolls [*Winterer and Sandwell,* 1987]. Searle et al. [1995] and Binard et al., [1996] describe morphologically similar ridges west of the Easter Microplate, which they also interpret to be caused by lithospheric tension but in this case, due to thermal, tectonic or volcanic load processes. For the formation of the Pukapuka ridges in the Central Pacific, Sandwell et al. [1995] propose a diffuse extension model which they relate to slab-pull forces affecting the Nazca and Pacific plate boundaries.

In the last decades, several near-axis topographic lineaments and seamount chains within a range of 0-200 km distance to the Mid-Atlantic Ridge (MAR) or East-Pacific Rise (EPR) have been described with orientations that likewise cannot be explained by either absolute or relative plate movement. Small [1995] suggests that a hotspot may be incrementally attracted by the center of an approaching spreading segment producing oblique volcanic trails as observed e.g. at Hollister Ridge, located obliquely between the EPR and the Louisville hotspot track. Other than described by Morgan [1978], in his model the deflected plume channel erupts on the ridge flanks and only in the latest stage on the ridge axis, where the melt is spread along the axis terminating the volcanic trail. From geochemical studies Geli et al. [1998] and Vlastelic et al. [1998] show evidence that excludes a contribution of the Louisville hotspot to Hollister Ridge. They relate the volcanism to intraplate deformation processes.

The ridge trends observed by Schouten et al. [1987] and Clague et al. [2000] near the EPR and MAR again fit perfectly to the trend predicted by Morgan's vector diagrams, although the appearance of the ridges seems to exclude hotspot influence. The axis-parallel motion component of the hotspot is replaced here by a sub-axis asthenosphere flow that equals the motion of the hotspot frame (but not a certain hotspot) with respect to the ridge and the authors interpret the structures to be generated by the migration of asthenosphere-entrained volcanic segments along the ridge. One of the most prominent examples for the off-axis formation of volcanic ridges due to hotspot-ridge interaction is the eastern tip of the Foundation Seamount chain [*O'Connor et al.,* 1998]. Here, the production of individual seamounts produced by the Foundation hotspot switches to elongated ridges as the Pacific-Antarctic Ridge (PAR) approaches the hotspot [*Maia et al.,* 2000]. This behavior is interpreted to reflect the onset of plume-asthenosphere channeling towards the PAR. Most studies on aseismic ridges are based on hydroacoustic and gravimetric measurements. Deeply penetrating seismic investigations revealing deep crustal structures of aseismic ridges have recently been conducted at the Ninetyeast Ridge [*Grevemeyer et al.,* 2001], Cocos Ridge [*Walther,* 2001], Carnegie Ridge [*Flueh et al.,* 2001], Nazca Ridge [*Bialas and Kukowski,* 2000], and Faroe-Iceland Ridge [*Staples et al.,* 1997]. These ridges are formed at spreading centers interacting with a near or on-axis hotspot which results in the typical azimuthal orientation following the projection of the hotspot track and the spreading direction.

The Musicians seamount region (Fig. 1), which is the target of this study, is characterized by a number of roughly W-E trending ridges whose origin is still under discussion. The ridges are slightly oblique to the former relative plate movement and also do not fit the absolute Pacific Plate movement. Epp [1978, 1984] proposed a creation of the ridges by flow of hotspot magma into weak transform faults that parallel the major fracture zones. This interpretation was reinforced in a tectonic reconstruction for the Pacific and Farallon Plate evolution around 90 Ma by Sager and Pringle [1987]. The authors argue that a change in spreading direction might have induced extension along fracture zones, where magma ascended to the surface. The Musicians elongated ridges are situated west of the former Pacific-Farallon spreading center position and do not extend beyond the trail of the Euterpe hotspot to the west (so termed by Flueh et al. (1999) after a muse of musicians in Greek mythology), suggesting that they might be a direct expression of plume-ridge interaction. We propose that the ridges were formed by off-axis volcanism on top of a sub-lithospheric melt flow from the hotspot to the Pacific-Farallon spreading center as this model explains most of the observed features. We use new seismic wide angle and swath bathymetric data to investigate the impact of this kind of volcanism on the crustal structure and morphology and propose a reconstruction model for the Mesozoic Pacific in the Musicians province based on two independent geomorphologic observations.

2. Tectonic setting

The Musicians seamounts are located several hundred kilometers northwest of the Hawaiian chain (Fig. 1). They are separated into a northern and a southern volcanic province by the Murray fracture zone. Seafloor mapping based on satellite altimetry [*Sandwell and Smith,* 1997] reveals several elongated volcanic ridges (VERs), which contain isolated volcanic summits along their crests. The lateral extent of the ridges increases southwards in the northern and southern provinces, respectively (Fig. 1) from less than 100 km to more than 400 km length. Two of the most prominent ridges, the northern Italian Ridge and the southern Bach Ridge (Fig. 1), both trending in a W-E direction nearly parallel to the pronounced fracture zone in their vicinity, are the focus of this study. Their seamounts are found in variable water depths of 2.2 km to 5.1 km (Fig. 2). The Murray Fracture Zone, which crosses the Musicians Province, is approximately 130 km wide (Fig. 3) and displays a ridge-and-trough morphology. As no discernable offset of the Musician seamounts across the fracture zone is observed, several authors [*Freedman and Parsons,* 1986; *Sager and Pringle,* 1987] have suggested that the Musicians were emplaced after fracture activity ceased.

A linear, 327° trending volcanic chain defines the western boundary of the Musicians province, where the elongated volcanic ridges are only recognized to the east and distinctly terminate at the Cretaceous Euterpe hotspot track. Ar-Ar age datings from Pringle [1992] confirm the hotspot hypothesis for this chain and reveal ages between 96 Ma in the north and 82 Ma in the south with a progression rate of 57 km/Ma, which makes it one of the oldest hotspot tracks on the Pacific plate. The Euterpe hotspot track terminates at the Pioneer Fracture Zone (Line 'A' in Fig. 3), which parallels the Mendocino Fracture Zone to the north (Fig. 3). Prior to 96 Ma, the hotspot trail altered the Farallon plate north of the large offset (800-1000 km) Mendocino transform fault before the northwestward moving Pacific Plate moved over the hotspot. Today, all traces on the Farallon plate have vanished since its track has been subducted underneath North America [*Sager and Pringle,* 1987].

The age of the underlying Pacific crust is not clear, as it is formed during the 'quiet' period of the earth magnetic field in the Cretaceous (approx. 118-83 Ma) when the Earth's magnetic field did not reverse its polarity. Extrapolation of the magnetic anomalies by Mueller et al. [1997] yields crustal ages beneath the Musician Seamount Province of approximately 110 Ma with a period of extremely rapid spreading between 120-110 Ma followed by slower spreading with only 1/3 of the rapid opening rate. This would imply that the Musicians were formed on approximately 15 Ma old crust. Freedman and Parsons [1986] propose a much younger age of the seafloor at the time of the seamount emplacement. Their investigations on the crustal elastic thickness yields a lithospheric age of less than 5 Ma at the time the Musicians were formed [*Freedman and Parsons,* 1986].

3. Data acquisition and processing

The HULA field campaign conducted with the German RV SONNE in 1999 [*Flueh et al.,* 1999] investigated two of the most prominent Musicians ridges in detail. To classify their type of volcanism with reference to other marine volcanic ridges and examine the formation of these ridges, the northern Italian Ridge and the southern Bach Ridge have been covered with wide-angle seismic, magnetic (Bill Sager, manuscript in prep., 2002), and hydroacoustic measurements. Geochemical analyses and age dating of several dredge samples along the ridges is still in progress. Here, we present seismic wide-angle data that were collected along three lines across the ridges supplemented by high-resolution swath bathymetric images of the entire length of Italian and Bach Ridge. The seismic lines (Fig.1) are between 180 and 220 km long and on each of them, 12-14 OBH (Ocean Bottom Hydrophones) were placed in the central part of the lines with a mean spacing of 5 km. We used two Bolt air guns with a total volume of 64 l as seismic source. With a shot interval of 60 s and a speed of 4 kn, a shot spacing of about 120 m was achieved. The data were recorded after anti-alias filtering at a sampling rate of 5 ms. In contrast to a well-tuned air gun array, the two large guns produced a rather oszillating signal. However, the seismic signal could be improved significantly by a processing sequence that was adapted to the special data characteristics. We applied a time-gated Wiener deconvolution with a gate length of 2 s. Filtering of wide-angle seismic records has to be done carefully, as the frequency content differs not only with travel time but also laterally with the travel path, whereas attenuation in the water column is neglectable. To account for these difficulties we applied a static water depth correction of the traces prior to an offset and time dependent frequency filter.

High-resolution hydroacoustic seafloor mapping was conducted along the Italian Ridge and the Bach Ridge (Fig. 2) using RV SONNE's onboard Hydrosweep multibeam system [*Grant and Schreiber,* 1990] with a 90° beam angle. Subsequent processing of each sweep was carried out using mbsystem [*Caress and Chayes,* 1996] and gmt [*Wessel and Smith,* 1991]. Sound velocity was determined by CTD measurements [Flueh et al., 1999].

4. Morphology of the Musicians Volcanic Elongated Ridges (VERs)

Global satellite altimetry data [*Sandwell and Smith,* 1997] suggest the Musicians to consist of mostly continuous ridges trending W-E. The new bathymetric data reveal details of the ridge morphology. In Figure 2, the 'predicted bathymetry' [*Sandwell and Smith,* 1997] is overlain by the high-resolution swath mapping data of Italian Ridge and Bach Ridge. The general 90° trend is overlain by oblique en-echelon segments trending about 84°, most obvious at the Italian Ridge in Fig. 2b. The ridges have a mean height of 2000 m and are dominated by prominent volcanoes emerging to a maximum height of 3500 m above the surrounding seafloor with a spacing from 30 km to 80 km. Despite these dominating volcanoes, the structure is significantly different from the Vance, President Jackson and Taney near-ridge seamounts in the northeastern Pacific as described by Clague et al. [2000], which consist exclusively of circular, isolated seamounts on a linear chain. The overall morphology of the Musicians is rather rough. The volcanism is fairly focused on dedicated ridges, similar to those at the Pukapuka ridges in the central Pacific [*Sandwell et al.,* 1995], but there are also several small volcanic cones with diameters between of 3 and 6 km on the plane seafloor nearby (Fig. 2). Diffuse lithospheric extension has been proposed as the origin process for the Pukapuka ridges [*Sandwell et al.,* 1995], however, the investigated ridges are elongate in the direction of present absolute plate motion, which is not the case for the Musician VERs.

The swath data give clear evidence for at least one major flat-top seamount on Italian and on Bach Ridge, respectively. Guyot 1 (Rossini seamount, Fig. 2a) at the western tip of Italian ridge emerges from the surrounding seafloor by 2950 m. Its shape is ESE-expanded and the flat top measures 11 km x 3 km. Guyot 2 is located on the eastern part of Bach Ridge with a height of 2650 m above seafloor level (Fig. 2 c). The circular flat summit, 3 km in diameter, is part of an ENE-elongated ridge segment. Both Guyot summits reach to a water depth of about 2700 m. Nevertheless, they display different relative heights resulting from different depths of the surrounding seafloor, as the southern part of the Musicians is 300 m shallower due to the younger lithosphere south of the Murray FZ and the influence of the nearby Hawaiian swell. The highest volcanoes on the two investigated ridges are labeled with water depths in Figure 2 (a) and (c). They have non-eroded tops and. particularly on Bach Ridge, they exceed the height of the Guyots by some hundred meters.

The relation of the Musicians Ridges to the adjacent fracture zones is enigmatic. Because of plate reorganizations in the Cretaceous, the major North Pacific fracture zones show a complex pattern with multiple changes from single fractures to broad scattered relay zones around the Musicians. Nevertheless, the interpolation of the Pioneer and Murray fracture zones as done from the satellite altimetry dataset in Figure 3 shows that their trends around the northern Musicians region correspond perfectly to each other: A simple shift of the Pioneer FZ trend (line 'A' in Fig. 3) matches the northernmost trace of the Murray FZ (line 'B'). The orientation of the southern Musicians ridges is roughly parallel to the Murray FZ, but from SE to NW, the fractures are getting increasingly oblique and the Musicians ridges do not follow this trend. Instead, their orientation remains constant (about 89°) in the whole area, regardless of the fracture trend. As seen in Figure 3, at the northern Italian Ridge the trend deviation is approximately 8°.

5. Tomographic inversion method

The seismic sections (examples presented in Figs. 4 and 5) show good quality data for the three seismic lines. Most of the stations have clear recordings in the whole shot-receiver offset range, up to a maximum of 140 km (e. g. OBH 35 and 47 in Fig. 5). Only in the central part of line 4, some stations display a lower signal-to-noise ratio attenuating phase coherency beyond 50-70 km offset. The seismic sections are strongly affected by the bathymetry of the ridges causing drastic changes in apparent velocities. However, the upper crustal refraction (Puc), lower crustal refraction (Plc) and mantle refraction (Pn) can be clearly differentiated on almost every station and reveal relatively smooth interval velocity structures across the ridges.

We used the FAST tomography code [*Zelt and Barton,* 1998] for our computations. This method is a first-arrival tomography utilizing the 'regularized inversion' on a uniform velocity grid. The velocity models were defined with a grid size of 2 km in x and 0.5 km in z direction. In total, more than 8000 first-arrival travel time picks per line were used for the inversions. The first arrivals up to ~25 km offset are related to upper crustal refractions (phase Puc in Figs. 4 and 5) and merge with only gradual velocity changes into the lower crustal refractions Plc. Together with the mantle reflection PmP these extend to large offsets of up to 100 km with high amplitudes, which is a distinct phenomenon of this dataset (e. g. OBH 09 and OBH 30 in Fig. 4). Between 40 and 100 km, the lower crustal refractions Plc are 'covered' as second arrivals behind the first-arrival mantle refraction Pn. A standard inversion of these travel times using a first arrival tomography scheme would take primarily the upper crustal and the mantle arrivals into account, but there are two problems with this approach: First of all, particularly with this dataset, nearly 1/3 of the travel time information would not be considered when omitting the second arrival refractions between 40 and 100 km offset (i.e. phase Plc), thus resulting in a poor resolution of the lower crust. Secondly, tomographic inversions of active seismic experiments often fail in reproducing upper mantle structures. The forward calculation technique used in the FAST code is capable of handling large velocity contrasts [*Hole and Zelt,* 1995], but a grid-based inversion generally must seek for a smooth solution to explain the observed travel times and fails in resolving sharp velocity contrasts like the crust-mantle boundary. Furthermore, the requirement of a uniform ray coverage is violated by the special geometry of the Pn phases. To overcome these problems the following approach was employed: In order to keep the starting model as simple as possible, we generated a normal oceanic crust velocity model with laterally constant v(z) dependence below the seafloor, according to the 'minimum 1D-model' of Kissling et al. [1994]. As a pure 1D structure would be rather unrealistic at the volcanic dome, the model is adjusted to the known bathymetry and to a realistic 2D structure at the central volcano as shown for line 2 in Figure 6. The approximate travel time fit of the model was achieved by forward ray tracing [*Zelt and Smith,* 1992], and computation of RMS misfits for different models was used to select the best starting model. The resolution of the computed inversion image could be improved by using a 'layer stripping' inversion method with three iterations. In the first step, only travel time picks with offsets up to 25 km were taken into account, yielding an image of the upper crust. Upper crustal velocities were held fixed in the next iterations. In a second step only offsets greater than 25 km have been inverted, aiming at the recovery of lower crustal velocities. The rays through the lower crust are mostly represented by secondary arrivals behind the mantle refraction (Pn). Therefore, the mantle phases have been omitted in this step. Consequently, also the mantle had to be omitted in the starting model resulting in a crust of infinite thickness as shown in Figure 6. The last step then consisted of an inversion for mantle velocities. Forward raytracing of the mantle phases PmP and Pn was used to define the depth of the Moho, which during a subsequent inversion of the mantle re-