Pulsing of a focused mantle plume: Evidence from the distribution of Foundation Chain hotspot volcanism

John M. O’Connor
GEOMAR – Research Center for Marine Geosciences, Christian-Albrechts University, Kiel, Germany

Peter Stoffers
Institute for Geosciences, Christian-Albrechts University, Kiel, Germany

Jan R. Wijbrans
Department of Isotope Geochemistry, Vrije Universiteit, Amsterdam, The Netherlands

Copyright 2002 by the American Geophysical Union.
0094-8276/02/2002GL014681, 2002

1. Introduction

[2] We report here new ⁴⁰Ar/³⁹Ar ages for linear volcanic structures scattered to the south of the Foundation Seamount Chain (Figures 1 and 2). This 22 Myr old volcanic trail records the motion of the Pacific plate over the narrow locus of the upwelling Foundation mantle plume [O’Connor et al., 1998, 2001, following Morgan, 1971]. Our ages (Table 1), supported by geochemical data [Hekinian et al., 1997, 1999; Hemond et al., 1999; Maia et al., 2001], show that these linear, disconnected structures are coeval with Foundation Chain seamount magmatism to the north and reveal that a ~250 km wide swath of scattered, coeval hotspot volcanism was created at 17 Ma by an apparently single short lived event related to the activity of the Foundation mantle plume (Figure 2). This new information allows us to compare variations in the temporal and spatial distribution of midplate volcanism created in a series of very different tectonic settings that are linked, in this case, to the migration of a fossil microplate over the Foundation plume [e.g., O’Connor et al., 1998, 2001]. We infer from this comparison that Foundation Chain development was controlled primarily by tectonic plate migration over broad zones of hot plume material of fundamentally constant size and orientation created with an apparent periodicity of about one Myr. This modified plume theory might also explain the widespread scattered midplate volcanism revealed recently in satellite altimetry mapping [Smith and Sandwell, 1997], given that many other mantle plumes are similarly pulsing large masses of hot plume material (not necessarily with the same periodicity or mass) into broad regions impacting the base of the Pacific lithosphere.

2. Distribution of Foundation Hotspot Volcanism

[3] Inferring long-term mantle plume behavior from the ~17 Ma magmatic event reported here (cf. Table 1) is supported by the fact that for at least the past 5 Myr the Foundation Chain developed in a series of similarly sized elongate (~250 km × ~150 km) swaths of disconnected coeval hotspot volcanism created at intervals of approximately 1 Myr [O’Connor et al., 2001]. Significantly, during the interval ~16 Ma to ~5 Ma the Foundation Chain formed as a narrow chain of seamounts, in contrast to the broad regions of scattered coeval magmatism created before and afterwards [O’Connor et al., 1998]. We explain this major switch in morphology in terms of the age, and consequently thickness and strength, of the seafloor migrating over the Foundation plume acting as a threshold parameter controlling the mode of hotspot volcanism. This is suggested by the similarity in age (~6 Myr) of the oceanic plate drifting over the Foundation plume at the onset of both episodes of broadly distributed hotspot volcanism at ~22 Ma and again at ~5 Ma (Figure 3). Nonetheless, our current and previous dating [O’Connor et al., 1998, 2001] demonstrates that the strict periodicity of Foundation Chain creation is not influenced by the changes in surface expression of hotspot magmatism.
Furthermore, we report here an $^{40}$Ar/$^{39}$Ar age (Table 1) for a rock sample dredged from the ‘failed’ spreading center of the Selkirk Microplate (Mammerickx, 1992; Tebbens and Cande, 1997). This process involved an eastward jump of a spreading center located east of the Foundation plume (‘failed’) and initiation of a ‘new rift’ [Mammerickx, 1992; Tebbens and Cande, 1997]. Contrastingly, the significantly younger ‘unmigrated’ seafloor was generated by normal seafloor spreading at the spreading center segment extending north of the ‘Failed Rift’. Variability in age of lithosphere drifting over, or close to, the Foundation plume is shown in Figure 3. Circles indicate dredge sites: black circles = $^{40}$Ar/$^{39}$Ar ages reported in this study (Table 1 and Supplemental Material), open circles = $^{40}$Ar/$^{39}$Ar ages reported in [O’Connor et al., 1998]. Measured ages are shown below dredge sample numbers. Rocks analyzed in this study were dredged from the Del Cano Lineament, a volcanic elongate ridge (VER) located further to the south, and the ‘Failed Rift’ of the Selkirk Microplate [Tebbens and Cande, 1997] during the 1997 N/O Atalante ‘Hotline’ cruise [Maia et al., 1997, 2001]. FSC = Foundation Seamount Chain; Bold blue lines = Failed Rift and IPF = Inner Pseudo Fault; FZ = Fracture Zone.

Furthermore, we report here an $^{40}$Ar/$^{39}$Ar age (Table 1) for a rock sample dredged from the ‘failed’ spreading center of the Selkirk Microplate (Figure 2) [Mammerickx, 1992; Tebbens and Cande, 1997] showing that it jumped eastward (failed) at 20.4 ± 0.3 Ma. This reveals that the process of Selkirk Microplate creation led to a large offset in the age of the seafloor that migrated later over the Foundation plume, resulting in the migration of seafloor ≤ 6 Myr only across the northern flank of the Foundation plume (Figure 3). Hotspot volcanism was restricted therefore to a narrow chain of seamounts between ~16 Ma and ~5 Ma, despite the inferred presence of much broader regions of Foundation plume material impacting periodically against the base of the Pacific plate. Another consideration is that seafloor in this region might also have been thermally reset to younger ages due to the

Figure 2. Red zones indicate the broad swath of scattered, structurally disconnected coeval Foundation hotspot magmatism produced during the ~17 Ma pulse (Table 1) of the Foundation mantle plume and the location of the hotspot at 20 Ma. The age of the seafloor labeled ‘migrated’ (older) was increased significantly by the creation of the Selkirk Microplate at 20 Ma (Table 1). This process involved an eastward jump of a spreading center located east of the Foundation plume (‘failed’) and initiation of a ‘new rift’ [Mammerickx, 1992; Tebbens and Cande, 1997]. Contrastingly, the significantly younger ‘unmigrated’ seafloor was generated by normal seafloor spreading at the spreading center segment extending north of the ‘Failed Rift’. Variability in age of lithosphere drifting over, or close to, the Foundation plume is shown in Figure 3. Circles indicate dredge sites: black circles = $^{40}$Ar/$^{39}$Ar ages reported in this study (Table 1 and Supplemental Material), open circles = $^{40}$Ar/$^{39}$Ar ages reported in [O’Connor et al., 1998]. Measured ages are shown below dredge sample numbers. Rocks analyzed in this study were dredged from the Del Cano Lineament, a volcanic elongate ridge (VER) located further to the south, and the ‘Failed Rift’ of the Selkirk Microplate [Tebbens and Cande, 1997] during the 1997 N/O Atalante ‘Hotline’ cruise [Maia et al., 1997, 2001]. FSC = Foundation Seamount Chain; Bold blue lines = Failed Rift and IPF = Inner Pseudo Fault; FZ = Fracture Zone.

Figure 3. (a). Correlation between Foundation Chain dredge site $^{40}$Ar/$^{39}$Ar ages and distance from the present Pacific-Antarctic spreading center. Also shown is the relationship between the Foundation Chain and the age of ‘migrated’ seafloor drifting directly over the hotspot (Figure 2). As the Selkirk Microplate reached the active hotspot region at about 14 Ma, increasingly older seafloor (≥ 6 Myr) began to cap the Foundation plume. This ‘older’ seafloor placed a sufficiently thick/strong lid over most of the region impacted by pulsed plume material to prevent the migration of plume melts to the seafloor during the interval ~14 Ma and ~5 Ma. The resulting transition from broad zones of hotspot volcanism to a narrow chain of seamounts is evident in Figure 2. Blue solid lines denote ‘older’ seafloor (unbroken lines indicate known seafloor ages [Mammerickx, 1992; Lonsdale, 1994]; blue dashed lines indicate extrapolated seafloor ages). The red swath indicates the broad zone of scattered coeval hotspot volcanism crosscutting the narrow Foundation Seamount Chain created by the 17 Ma pulse of the Foundation plume (Table 1). $^{40}$Ar/$^{39}$Ar ages shown as open spheres are from this study (Table 1 and Supplemental Material) and [O’Connor et al., 1998, 2001]. The solid line is the York-2 linear regression fit to previously published data representing an average rate for the migration of volcanism along the chain of 91 ± 2 mm/yr [O’Connor et al., 1998]. Analytical error bars are ±2σ. (b). Relationship between Foundation Chain and younger, ‘unmigrated’ seafloor. The spreading center north of the ‘Failed Rift’ likely continued spreading normally such that ‘younger’ (≤ 6 Myr) seafloor was migrating over the northern flank of the Foundation plume. This younger, ‘unmigrated’ seafloor drifting by the northern flank of the Foundation plume was sufficiently thin to allow the passage of plume melts along a narrow strip leading to creation of a correspondingly narrow chain of Foundation seamounts (Figure 2). Long green dashed line indicates younger, ‘unmigrated’ seafloor created by the spreading center north of the ‘Failed Rift’ (extrapolation of known seafloor ages west of the Selkirk Microplate).
preferential channeling of plume material [e.g., Morgan, 1978; Schilling, 1985, 1991] to the nearby spreading center responsible for this younger seamount.

[5] If the previously proposed relationship between the Foundation plume and older seamounts in the Austral Island region [McNutt et al., 1997; O'Connor et al., 1998] is correct (Figure 1), then the Foundation plume was active for at least the past 34 Myr. As in the case of the Foundation Chain, the lack of significant hotspot volcanism between the Foundation Chain and the >34 Myr Ngatamato and Taikina Seamounts [McNutt et al., 1997; Maia et al., 2001] can be explained by migration of seafloor that was too old and consequently too thick and strong (>6 Myr in the case of the Foundation plume) to allow Foundation plume magma to reach the lithospheric surface.

[6] We propose therefore that the development of broad swaths of coeval hotspot volcanism, with an apparent periodicity of approximately 1 Myr, is related primarily to the long-term dynamics of the Foundation plume since at least 34 Ma. This activity is characterized by periodic emplacement of large masses of hot plume material (pulsing) into broad, similarly sized and oriented zones (focused at least on initial impact at the base of the Pacific tectonic plate). The pattern of hotspot volcanism produced within each such ‘zone’ was controlled by localized factors such as lithospheric age and stress [McNutt et al., 1997; Hieronymus and Bercovici, 2000; Maia et al., 2001; O’Connor et al., 2001]. However, involvement of pre-existing lithospheric structures acting as ‘weak zones’ facilitating decompression melting of hot plume material is strongly indicated by the fact that volcanic lineaments south of the Foundation Chain parallel the local fracture zone (FZ) direction (Figure 2).

3. Implications for Plume Modeling

[7] We cannot resolve differences in age across individual, similarly sized and oriented, zones of Foundation midplate volcanism created at a rate of approximately once per Myr. A physical process is therefore required that periodically brings masses of hot plume material extremely fast from depth and is capable of focusing it into broadly elongate zones (~250 km × ~150 km), at least on initial impact against the base of the drifting Pacific plate. Depth-dependent properties have been shown theoretically to play an important role in controlling plume dynamics [Hansen et al., 1993]. For example ‘ultrafast’ focused mantle plumes are theoretically possible in the upper mantle during thermal convection with a non-Newtonian temperature- and depth-dependent rheology operating at a reasonable effective Rayleigh number on the order of $10^8$ [Larsen and Yuen, 1997; Larsen et al., 1999]. Such strong depth-dependence in viscosity also results in masses of plume material pulsing at intervals ranging from a few Myr [Larsen et al., 1999] to about 10 Myr [Larsen and Yuen, 1997] with calm periods in between [Larsen et al., 1999]. These current models indicate that plumes can rise through the upper mantle in much less than one Myr [e.g., Larsen et al., 1999], so providing a mechanism by which hot plume material can be brought from the transition zone to the lithosphere extremely fast (m/yr) in an otherwise slowly convecting mantle (cm/yr). Following impact against the base of the lithosphere this material can flow laterally at rates as high as ~ 0.5 m/yr, so creating the potential of coeval magmatism scattered over large areas [Larsen and Yuen, 1997; Sleep, 1997; Larsen and Saunders, 1998; Larsen et al., 1999]. Our results suggest that SE Pacific mantle plumes are more tightly focused and faster pulsing than is presently incorporated into such numerical models indicating even greater viscosity stratification (or changes in the creep law) across the upper mantle compared to, for example, the region of the North Atlantic influenced by the Iceland plume [e.g., Larsen et al., 1999; O’Connor et al., 2000].

4. Discussion and Conclusions

[8] Prior to this study it was not possible to determine whether the elongate ‘zones’ of scattered coeval hotspot volcanism at the young end of the Foundation Chain [O’Connor et al., 2001] are the expression of the long-term dynamics of the Foundation mantle plume. We resolve this fundamental question by 1) showing that Foundation hotspot volcanism occurred within similarly sized elongate ‘zones’ prior to the migration of the fossil Selkirk Microplate over the Foundation plume hotspot, and 2) suggesting a possible mechanism to explain why only a narrow chain of seamounts developed across these elongate ‘zones’ during the interval between microplate migration over the plume hotspot at ~14 Ma and the onset of volcanic elongate ridge (VER) development ~5 Myr ago.

[9] We explain therefore the distribution of Foundation midplate volcanism in terms of a mantle plume pulsing hot masses with an apparent periodicity of approximately 1 Myr. Material associated with individual pulses is focused (at least on initial impact against the base of the lithosphere) into basically similarly sized and oriented elongate ‘zones’. Variations in the age, structure and stress pattern of tectonic plates (e.g., migration of the Selkirk Microplate over the plume hotspot and plume-spreading-center interaction) driving over pulsing mantle plumes control if and where hotspot volcanism develops on the Pacific plate. [10] Our model proposed here for Foundation plume volcanism could have implications for Pacific midplate volcanism in general. Variations in the age, structure and stress patterns of tectonic plates drifting over pulsing mantle plumes might control if and where
hotspot volcanism develops on the Pacific plate, so leading to the development of broad swaths of scattered hotspot volcanism that often crosscut prominent seamount chains. Furthermore, this previously unknown, episodic/periodic emplacement of broad synchronous regions of hot plume material under Pacific tectonic plates, far larger than suggested by narrow seamount chains such as Hawaiian-Emperor, has important implications for measuring the activity of mantle plumes and for testing numerical models of plume dynamics and mantle circulation.

[11] Acknowledgments. We thank Captain J.-C. Gourmelon and crew of the N/O Atalante for fine ship operation and the scientific party for help with dredging and on board sample preparation. R. Hekinian is acknowledged for leading the dredge-sampling program. D. Ackerman, A. Dehghani, R. Hekinian, J. Phipps Morgan, D. Naar, and D. Sandwell are thanked for helpful discussions during the ‘Foundation Hotline’ cruise. We thank two anonymous reviewers for very helpful comments. This work was supported by BMBF projects 03G0100A0 and 03G0157A (P.S.) and INSU-CNRS. The contribution of JRW is covered by NSG #20020302.

References


J. M. O’Connor, GEOMAR-Research Center for Marine Geosciences, Christian-Albrechts University, Wischhofstr. 1-3, Kiel, D-24148, Germany. (jomoconnor@geomar.de)

O’Connor, J. M., Department of Geosciences, Christian-Albrechts University, Kiel, D-24118, Germany.

J. R. Wijbrans, Department of Isotope Geochemistry, Vrije Universiteit, Amsterdam 1081 HV, The Netherlands.