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RESEARCH NOTE

Crustal underplating and its implications for subsidence and state of isostasy along the Ninetyeast Ridge hotspot trail

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SUMMARY

Recent seismic field work has revealed high lower-crustal velocities under Ninetyeast Ridge, Indian Ocean, indicating the presence of crustal underplating (Grevemeyer *et al.* 2000). We used results from Ocean Drilling Program (ODP) drill cores and cross-spectral analysis of gravity and bathymetric data to study the impact of the underplating body on the subsidence history and the mode of isostatic compensation along Ninetyeast Ridge. Compared with the adjacent Indian basin, the subsidence of Ninetyeast Ridge is profoundly anomalous. Within the first few millions of years after crustal emplacement the ridge subsided rapidly. Thereafter, however, subsidence slowed down significantly. The most reliable model of isostasy suggests loading of a thin elastic plate on and beneath the seafloor. Isostatic compensation of subsurface loading occurs at a depth of about 25 km, which is in reasonably good agreement with seismic constraints. Subsurface loading is inherently associated with buoyant forces acting on the lithosphere. The low subsidence may therefore be the superposition of cooling of the lithosphere and uplift due to buoyant material added at the base of the crust. A model including prolonged crustal growth in the form of subcrustal plutonism may account for all observations.

Key words: crustal structure, hotspots, isostasy, subsidence.

INTRODUCTION

Hotspot-related volcanism in active continental rift zones or on rifted continental margins is frequently associated with unusually high lower-crustal velocities, indicating the presence of large plutonic complexes at the base of crust (e.g. Coffin & Eldholm 1994). Crustal underplating at oceanic plateaus, submarine ridges or seamounts may affect the subsidence history (e.g. Ito & Clift 1998) or isostatic compensation (e.g. Watts & ten Brink 1989; Wolfe *et al.* 1994) at these features. Until a few years ago, however, seismic evidence for crustal underplating at oceanic plateaus or seamounts was limited to the Hawaiian (ten Brink & Brocher 1987; Watts *et al.* 1985) and the Marquesas islands (Caress *et al.* 1995). Therefore, the only comprehensive study on crustal underplating, isostasy and subsidence was focused on the Hawaiian Islands (Watts & ten Brink 1989). In 1998, however, a seismic survey at Ninetyeast Ridge clearly indicated a subcrustal plutonic complex under this major Indian Ocean hotspot track (Flueh *et al.* 1999a; Grevemeyer *et al.* 1998, 2000). In order to gain a better understanding of the impact of this underplated body on the subsidence and isostatic compensation, we used data from Ocean Drilling Program (ODP) leg 121 (Peirce *et al.* 1989) to constrain the subsidence history, and shipboard bathymetry, along with gravity anomalies, to evaluate the state of isostasy along Ninetyeast Ridge.

GEOLOGICAL BACKGROUND

Tectonic settings

Ninetyeast Ridge is a major aseismic ridge that can be traced for about 5000 km from latitude 30°S northwards into the Bay of Bengal (Fig. 1), where it is buried beneath the Bengal Fan. This remarkably linear and nearly meridional ridge varies in width from 100 to 200 km and is elevated by about 2 km compared with the adjacent ocean basins. Palaeontological, palaeomagnetic and radiometric studies of rock samples from

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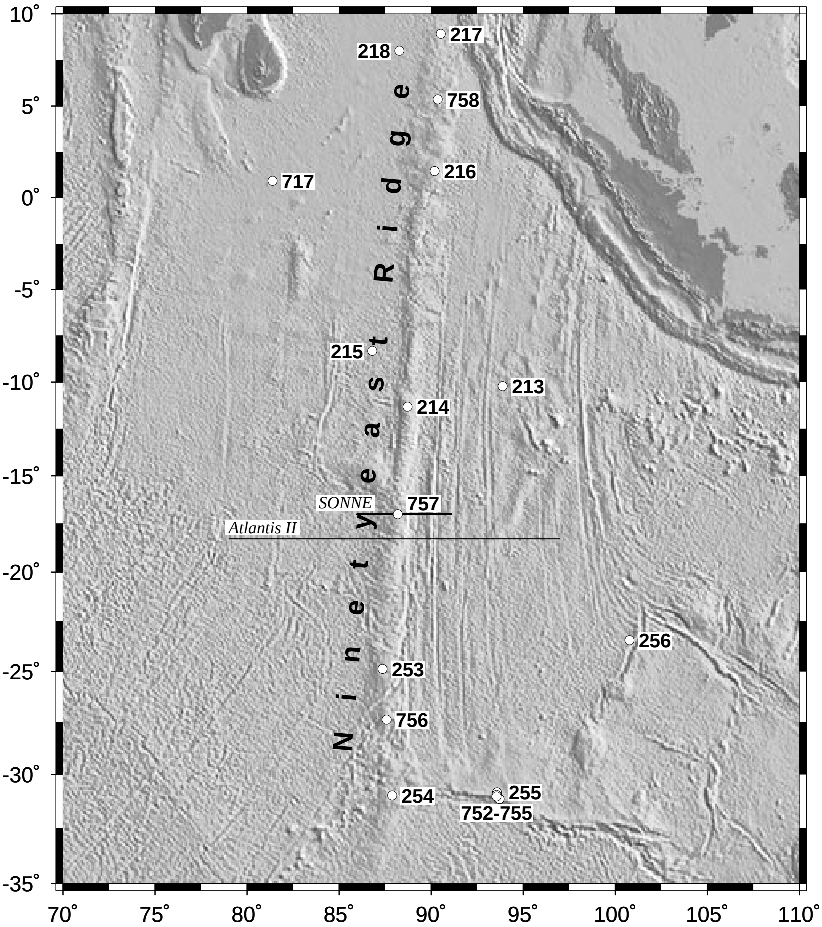

Figure 1. Predicted bathymetry of the central Indian ocean (Smith & Sandwell 1997) showing Ninetyeast Ridge and the *Sonne* profile where recent seismic field work reveals crustal underplating (Grevemeyer *et al.* 1998, 2000). Immediately to the south, the *Atlantis II* crossed the hotspot track. Circles are Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) holes.

Deep Sea Drilling Project (DSDP) legs 22 and 26 and ODP leg 121 indicate that basement ages become older in a northward direction from approximately 38 Ma at DSDP site 254 near the southern terminus to 80–82 Ma at the most northerly ODP site 758 near 5°N (Peirce 1978; Royer *et al.* 1991; Duncan 1991). The general northerly increase in age relates Ninetyeast Ridge and the 117 Ma Rajmahal traps onshore Bangladesh to a long-lived hotspot that progressively built both features on the Indian plate as the plate drifted northwards (Morgan 1981; Duncan 1991; Royer *et al.* 1991). Basement palaeolatitudes from most DSDP and ODP sites indicate that the hotspot plume remained at a constant latitude near 50°S, the present location of the Kerguelen hotspot (Peirce 1978; Royer *et al.* 1991).

Seismic constraints

In the spring of 1998 the German research vessel *Sonne* carried out a large seismic refraction and wide-angle survey on Ninetyeast Ridge (Flueh & Reichert 1998; Flueh *et al.* 1999a). The data were acquired near ODP site 757, drilled during ODP leg 121, and indicate that the adjacent ocean basins are typically oceanic with a crustal thickness of about 6.5–7 km. Approaching Ninetyeast Ridge, the crust thickens to about 24 km. Wide-angle reflections from both the top and base of a 7.5–7.6 km s^{-1} body clearly indicate hotspot-related underplating and suggest that subcrustal plutonic complexes comprise an integral part of the hotspot trail (Grevemeyer *et al.* 1998, 2000).

SUBSIDENCE HISTORY

To assess the subsidence of Ninetyeast Ridge we had to constrain the depth of sedimentation. In our analysis we follow the approach of Ito & Clift (1998). They used microfossil data, especially benthic foraminifera, to estimate the palaeodepth and hence subsidence of large Pacific plateaus. Different species of benthic foraminifera are inherently related to a particular depth interval within which they could live. Usually, it is possible to discriminate among seven depth zones: subaerial, photic zone (depth = 0–50 m), shallow marine shelf (0–200 m), upper bathyal (200–500 m), mid bathyal (500–1500 m), lower bathyal (1500–3000 m) and abyssal (> 3000 m). Core-catcher samples from ODP leg 121 provided benthic foraminifers for sites 756, 757 and 758, and calcareous nannofossils and planktonic foraminifers provided biostratigraphic ages (Peirce *et al.* 1989). In addition, we corrected depth estimates for the effects of sediment loading by using the equation

$$d_C = d_W + t_S(\rho_S - \rho_M)/(\rho_W - \rho_M)$$

(Crough 1983), in which d_W is the water depth or depth of sedimentation, t_S is the thickness of sediment above the core providing the benthic foraminifera, and $\rho_W = 1050\,\mathrm{kg\,m^{-3}}$, $\rho_S = 1800\,\mathrm{kg\,m^{-3}}$ and $\rho_M = 3300\,\mathrm{kg\,m^{-3}}$ are the densities of water, sediment and mantle rock, respectively. However, a maximum sediment thickness of ~ 500 m was detected at site 758; consequently, the contribution of sediment loading to subsidence is generally small (< 340 m) and vanishes compared with the uncertainty of depth within which a particular species of benthic foraminifera is expected, especially for the lower bathyal and abyssal zones.

Fig. 2 summarizes the results. The time of the plume event was approximated using the age of drilled basement rocks as determined by Duncan (1991) from $^{40}Ar/^{39}Ar$ dating. Within the error bounds, this age is generally coincident with the age of the underlying Indian plate (Royer *et al.* 1991). This observation is supported by geochemical and isotopic studies of basalts drilled on Ninetyeast Ridge. The tholeiitic, iron-rich and voluminous character of basalts is typical of oceanic islands or seamounts associated with hotspots on or near a mid-ocean spreading centre (Saunders *et al.* 1991).

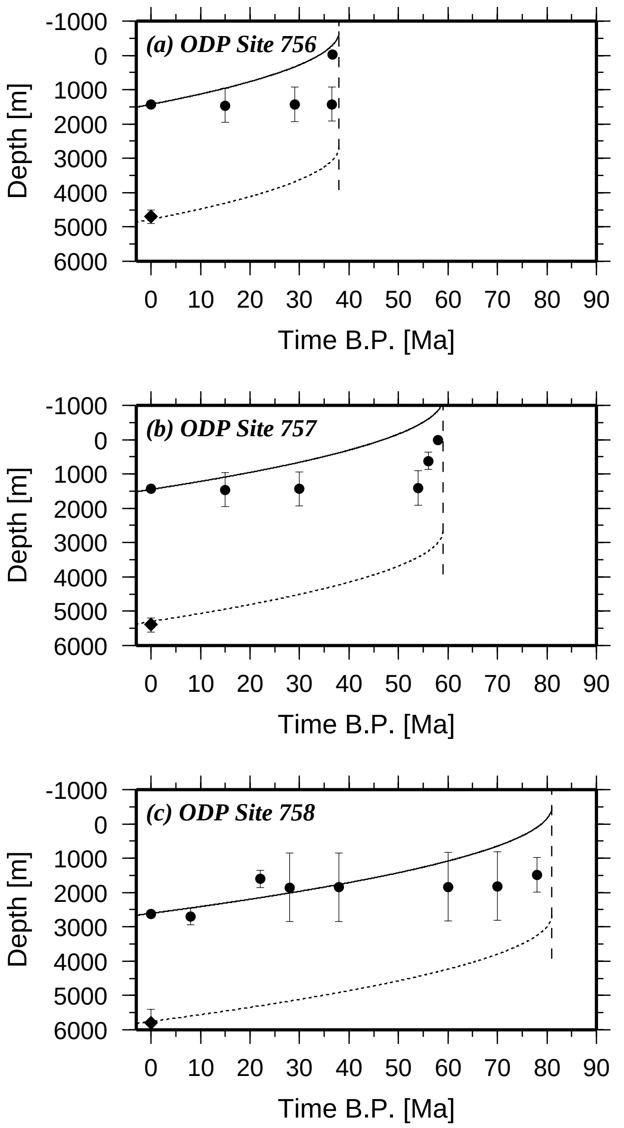

Figure 2. The thermal subsidence predictions of the Parson & Sclater (1977) model (dotted curves) are compared with reconstructed basement depths (solid circles) from benthic foraminifera found in ODP drill cores (Peirce *et al.* 1989). Different species of benthic foraminifera are inherently related to a particular depth interval within which they could live. Error bars give those intervals. The solid curve is a shifted model to point out the anomalous subsidence of the hotspot swell. Diamonds mark the present-day depth of unloaded basement adjacent to the drill sites in the Indian basin.

When compared with the Parson & Sclater (1977) prediction for normal seafloor, the observed abyssal basement adjacent to Ninetyeast Ridge indicates no bathymetic anomaly. As with the data from Ninetyeast Ridge, the depth estimates have been corrected for sediment thickness and loading. If possible, the thickness of sediments was derived from ODP and DSDP sites (see Fig. 1); otherwise, from related seismic reflection surveys. In contrast, the subsidence history of the ridge itself is profoundly anomalous. Sites 756 and 757 suggest a rapid initial subsidence within a few million years of formation. Thereafter, however, the subsidence of the ridge slowed down significantly. This fact can be most clearly seen by back-tracing the subsidence (Fig. 2). Even the Parson & Sclater (1977) curve indicates clear differences between reconstructions and model predictions. Using a hotspot model with elevated mantle temperatures (e.g. Ito & Clift 1998), the misfit would be even more pronounced. Thus, Ninetyeast Ridge shows no evidence for the subsidence that would be expected from thermal plume models, which assume rapid emplacement of hotspot tracks at elevated mantle temperatures (e.g. Crough 1978; Detrick & Crough 1978; Sleep 1990).

STATE OF ISOSTASY

The cross-spectral technique of analysing gravity and bathymetric data to constrain the state of isostasy at geological features has been established for a number of years (e.g. McKenzie & Bowin 1976; Watts 1978; Forsyth 1985; McKenzie & Fairhead 1997). Near 17°S at Ninetyeast Ridge, a recent *Sonne* cruise found clear seismic evidence for hotspot-related crustal underplating (Grevemeyer *et al.* 1998, 2000). The *Sonne* profile, however, is only 550 km long. To include long-wavelength features, we had to incorporate bathymetric data from an *Atlantis II* survey line (National Geophysical Data Center 1995) immediately to the south (Fig. 1), and gravity data from satellite altimetry (Sandwell & Smith 1997). Fig. 3 shows the gravity anomaly and bathymetry profiles. In order to test the significance of the observed admittance we checked whether the coherency differs appreciably from zero. Using the definition of McKenzie & Bowin (1976), we found that for wavenumbers of less than $0.25\,\mathrm{km^{-1}}$ the coherency^2 is well above 0.5.

Observed admittances with wavenumbers less than $0.2\,\mathrm{km^{-1}}$ were compared with theoretical admittances, which characterize various models of isostatic and dynamic compensation (Fig. 4). Four different models were calculated, namely an Airy-type model (McKenzie & Bowin 1976), and three models where an elastic plate is loaded (1) on the seafloor (McKenzie & Bowin 1976), (2) beneath the seafloor (subsurface load or underplating) (McNutt & Shure 1986), and (3) on and beneath the seafloor (Forsyth 1985; McAdoo & Sandwell 1989). In evaluating theoretical admittances for the four models, we only adjusted the crustal thickness T_c, the elastic thickness of the

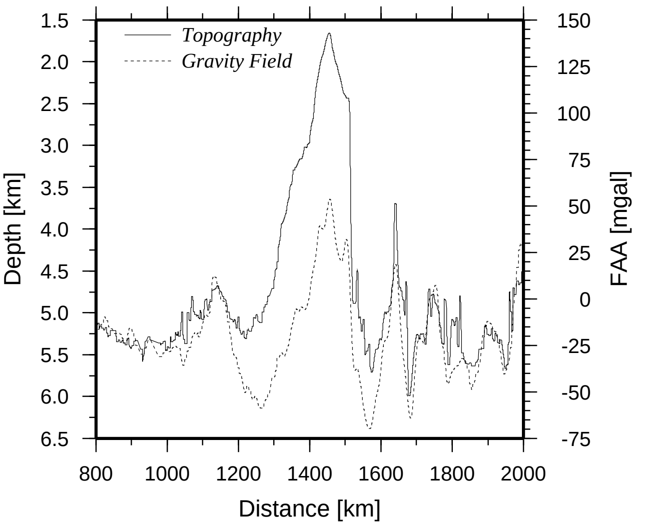

Figure 3. Gravity anomaly and bathymetry profiles over Ninetyeast Ridge. The location is indicated in Fig. 1.

lithosphere T_e, the compensation depth of the buoyant subsurface load Z_l (using $T_e = 5$ km), and the ratio of subsurface to surface load f (using $T_e = 5$ km and $Z_l = 25$ km), respectively. For the subsurface load and the model combining surface and subsurface loading, a reasonably thin elastic plate ($T_e = 5$ km) was chosen, because it is known from drilling that Ninetyeast Ridge was created on young and thus thermally thin lithosphere. All the other parameters given in the theoretical equations have been taken from McAdoo & Sandwell (1989).

An Airy-type model with a crustal thickness of $T_c = 30$ km, and an underplating model with a compensation depth of $Z_l = 25$ km are good agreement with the observed admittances, while the surface-loading models fit only the shorter wavelengths reasonably well (Fig. 4). The model considering both surface and subsurface loading, however, provided an excellent agreement for a ratio of subsurface to surface load of $f > 0.5$. It would normally be difficult to distinguish among these models; however, the seismic model presented by Grevemeyer *et al.* (2000) shows clear reflections from a pre-hotspot Moho, and their resulting model strongly supports the idea that a 6.5–7 km thick pre-hotspot crust was bent downwards by loading of the lithosphere. Subsequently, crust was underplated by material with seismic velocities between those of lower crustal mafic rocks and ultramafic upper mantle material. The base of this subcrustal plutonic complex was sampled by seismic wide-angle reflections. In addition, the Airy model with a mean crustal thickness of 30 km is not in accordance with the seismic data, which suggests that the maximum thickness of crust beneath Ninetyeast Ridge is about 24 km (Flueh *et al.*

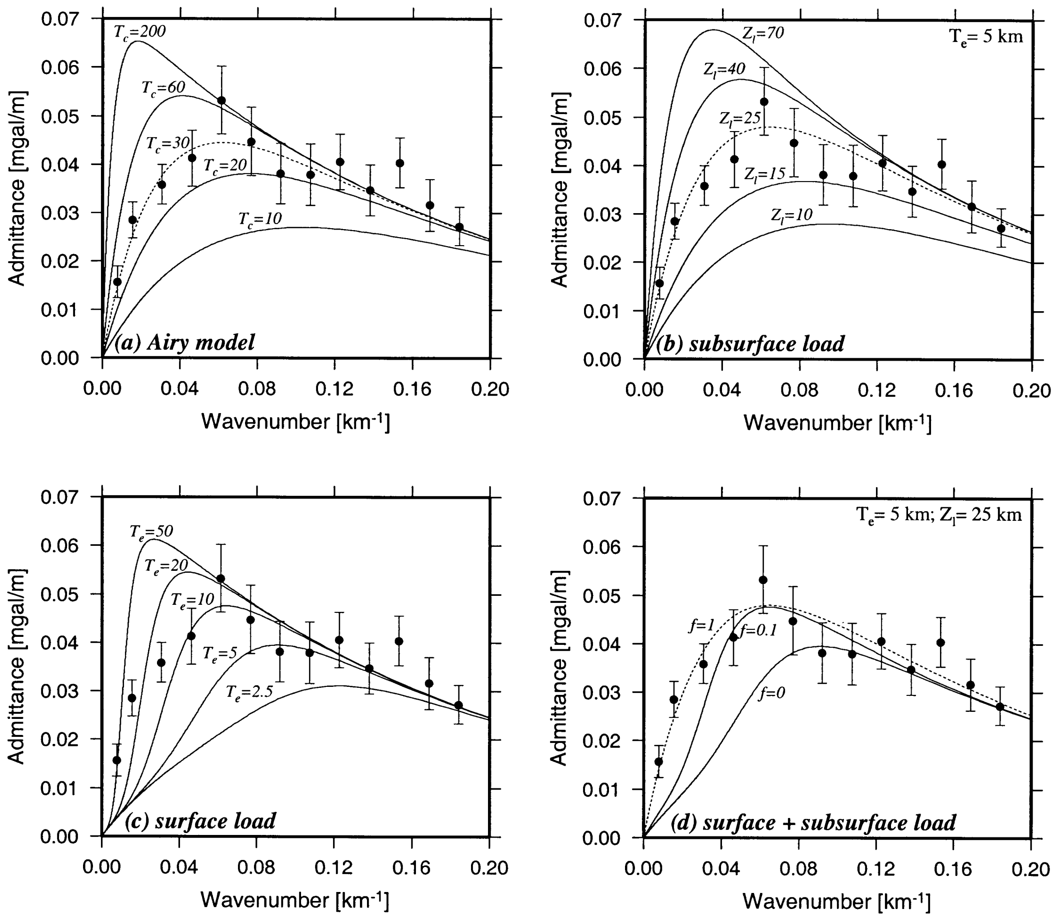

Figure 4. Admittance with standard error (solid circles with error bars) generated from gravity and bathymetry profiles over Ninetyeast Ridge (Fig. 3). The curves are theoretical models based on (a) an Airy model, (b) subsurface loading of an elastic plate, (c) surface loading of an elastic plate, and (d) loading of an elastic plate from above and below (see text for further description). Best-fitting models are indicated by broken lines.

1999a; Grevemeyer *et al.* 1998, 2000). Consequently, it is reasonable to favour the model where an elastic plate is loaded at and beneath the seafloor.

DISCUSSION AND CONCLUSIONS

A number of models have been developed to explain hotspot swell behaviour, and hence subsidence that can be described by either isostatic or dynamic-type models. Isostatic models, like those introduced by Crough (1978) and Detrick & Crough (1978), involve re-heating of the lithosphere, during which process the normal lithosphere is thinned by a plume such that it then subsides like lithosphere of a young age. Dynamic models, on the other hand, explain swell formation by viscous normal stresses imposed on the lithosphere by a rising plume. As the lithosphere is 'pulled away' from the plume source, the weakening normal stresses allow a rapid subsidence (e.g. Farnetani & Richards 1994; Ribe & Christensen 1994). These models have been successfully applied to describe, for example, the subsidence of the Hawaiian swell (Detrick & Crough 1978; Ito & Clift 1998). However, they fail to explain the anomalously low subsidence of Ninetyeast Ridge.

A critical issue in the discussion of the subsidence history is the depth at which the igneous basement was created. Drilling at site 757 suggests a shallow-water or subaerial environment for the basement (Peirce *et al.* 1989). This conclusion is supported by seismic reflection data, which reveal a wedge of dipping reflectors at the drill site (Flueh *et al.* 1999a, 1999b), stratigraphically similar to seaward-dipping reflectors imaged at volcanic continental margins (e.g. Hinz 1981; Mutter *et al.* 1982). Drilling of site 642 at the Voring volcanic margin off Norway also supports a shallow-water or subaerial environment (Planke 1994; Planke & Eldholm 1994). Seaward-dipping reflectors could not, however, have remained in a shoaling stage for a long time: if they did, they would have subsequently been eroded at the wavebase. The sequence imaged near site 757 is, however, quite well preserved.

At site 757 the $^{40}Ar/^{39}Ar$ age (though poorly constrained) of volcanic bedrock is 58 Ma (Duncan 1991). It is important to note that dating of the oldest sediments recovered at the drill site give the same age (Peirce *et al.* 1989). The sediments, however, were deposited in a marine environment. This fact is demonstrated by drilling that sampled above the basement volcaniclastic deposits created by phreatic volcanism. This sediment was probably derived from the small volcanic cones detected in swathmapping sonar and seismic reflection data eastwards of site 757 (Flueh & Reichert 1998; Flueh *et al.* 1998). These eruptive centres must have been active well below the wavebase, as otherwise they would have been eroded. Moreover, seismic refraction data do not provide any evidence for a large volcaniclastic apron (Flueh *et al.* 1999b; Grevemeyer *et al.* 2000), which would be expected if a seamount reached the shoaling stage and hence the critical depth for a drastic increase of exolution of magmatic volatiles, resulting in the formation of mainly clastic rocks (Staudigel & Schmincke 1984). Consequently, there is a consistent line of evidence suggesting that, at least at site 757, the ridge never formed an island, contrary to suggestions by other subsidence studies (e.g. Coffin 1992), but remained for most time of its life below sea level. The same holds for site 758, which provided only basalts emplaced in mid to deep water (Peirce *et al.* 1989). The best fit by back-tracing the subsidence was found for site 756. However, despite the large errors associated with the palaeodepth estimates, the depth of sedimentation between 18 and 35 Ma BP is not matched by the subsidence trend. Similar discrepancies are evident in the data from sites 757 and 758; thus, a simple subsidence model incorporating only cooling cannot explain the data.

As discussed above, the most reliable isostatic model is one combining loading of a thin elastic lithosphere from above and below. Its compensation depth of about 25 km is in excellent agreement with the Moho at the base of the underplating body (Flueh *et al.* 1999a; Grevemeyer *et al.* 1998, 2000). Thus, both the compensation depth of the subsurface load and the seismic data indicate the presence of material added at the base of crust. Subsurface loading, in turn, is associated with buoyant forces and thus provides an uplift of the lithosphere. Consequently, it is reasonable to suggest that underplating has an impact on the subsidence history. Ito & Clift (1998) emphasize this issue to explain the low subsidence of Pacific plateaus created over high-temperature and high-volume plume sources. In their model, plateau subsidence is the superposition of (1) subsidence due to the cooling of the plume source, and (2) uplift due to prolonged crustal growth in the form of magmatic underplating. This prolonged crustal growth and uplift scenario can explain the late-stage eruption on Pacific plateaus, the high-velocity lower crust, and the widespread normal faults observed throughout and along the margins of the plateaus. Ito & Clift (1998) proposed that such late-stage underplating may have occurred over a time of ~30 Ma.

The Ito & Clift (1998) scenario is a likely explanation for most observations from Ninetyeast Ridge. Consistently, we favour a model where a plume event rapidly emplaced large volumes of extrusives on a young and therefore thin elastic lithosphere. The isostatic rebound by loading a weak lithosphere may explain the rapid initial subsidence observed at ODP sites 756 and 757. As the Indian plate moved away from the plume source, prolonged crustal growth occurred primarily in the form of magmatic underplating. Material added at the base of crust introduced buoyant forces which may account for the anomalously low subsidence.

Generally it would be difficult and tenuous to assess the time interval within which late-stage plutonism may have occurred. The *Sonne* cruise, however, revealed that small volcanic cones are abundant around site 757 (Flueh *et al.* 1998). If these seamounts had been emplaced within a few million years after the subaerial or shallow marine emplacement of lavas drilled at site 757, they would have been eroded in shallow water. Consequently, they represent late-stage effusive volcanism and were formed after Ninetyeast Ridge had subsided by at least a few hundred metres. At site 757 rapid subsidence dominated for about 5 Ma. Thereafter, subsidence was reasonably low. Prolonged late-stage crustal growth therefore may have occurred for more than 5 Ma, maybe up to ~15 Ma, after the emplacement of the volcanic edifice. Additional constraints are available from the deep seismic data (Grevemeyer *et al.* 2000).

The southern Ninetyeast Ridge was emplaced along a transform plate boundary (Royer *et al.* 1991). This fact is documented by a steep escarpment to the east, which was created while Ninetyeast Ridge was pulled apart from Broken Ridge. The model of Grevemeyer *et al.* (2000) indicated crustal underplating extending under the Wharton Basin to the east of Ninetyeast Ridge. This clearly indicates that underplating continued after Ninetyeast Ridge and Broken Ridge had separated. The age offset across the fracture zone is ~5–10 Ma (which is poorly constrained) and thus possibly indicates about 15–20 Ma (or even longer) of prolonged crustal growth by underplating. Because the ridge was during that time part of the fast-moving Indian plate, the observations may indicate flow of hotspot material along the fossil hotspot trail, suggesting that existing paths of melt migration remain open and stable after the edifice was removed from its heat source (Grevemeyer *et al.* 2000).

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REFERENCES

Caress, D.W., McNutt, M.K., Detrick, R.S. & Mutter, J.C., 1995. Seismic imaging of hotspot-related crustal underplating beneath the Marquesas islands, *Nature,* **373,** 600–603.

Coffin, M.F., 1992. Emplacement and subsidence of Indian ocean plateaus and submarine ridges, in *Synthesis of Results from Scientific Drilling in the Indian Ocean,* eds Duncan, R.A., Rea, D.K., Kidd, R.B., von Rad, U. & Weissel, J.K., *Geophysical Monograph,* **70,** 115–125, American Geophysical Union, Washington.

Coffin, M.F. & Eldholm, O., 1994. Large Igneous Provinces: crustal structure, dimensions, and external consequences, *Rev. Geophys.,* **32,** 1–36.

Crough, S.T., 1978. Thermal origin of mid-plate hotspot swells, *Geophys. J. R. astr. Soc.,* **55,** 451–469.

Crough, S.T., 1983. The correction for sediment loading on the seafloor, *J. geophys. Res.,* **88,** 6449–6454.

Detrick, R.S. & Crough, S.T., 1978. Island subsidence, hotspots and lithospheric thinning, *J. geophys. Res.,* **83,** 1236–1244.

Duncan, R.A., 1991. Age distribution of volcanism along aseismic ridges in the eastern Indian ocean, *Proc. ODP Init.* Rep. **121,** 507–517.

Farnetani, C.G. & Richards, M.A., 1994. Numerical investigations of the mantle plume interaction model for flood basalt events, *J. geophys. Res.,* **99,** 13 813–13 833.

Flueh, E.R. & Reichert, C., eds, 1998. Cruise Report SO131, SINUS – Seismic investigations at the Ninetyeast Ridge observatory using SONNE and JOIDES RESOLUTION during ODP leg 179, *GEOMAR Report,* **72.**

Flueh, E.R., Kläschen, D., Weinrebe, W. & Reichert, C., 1998. Investigation of small submarine volcanic cones at Ninetyeast Ridge by high resolution seismic investigations and bathymetry, *EOS, Trans, Am. geophys. Un.*, **79** (Fall mtg suppl.), 872.

Flueh, E.R., Grevemeyer, I. & Reichert, C., 1999a. Ocean site survey reveals anatomy of a hotspot track, *EOS, Trans. Am. geophys. Un.,* **80,** 77.

Flueh, E.R., Grevemeyer, I. & Reichert, C., 1999b. Investigating the crustal framework at the NERO hole 1107A, Leg 179, *JOIDES J.,* **25** (1), 14–16.

Forsyth, D.W., 1985. Subsurface loading and estimates of the flexural rigidity of continental lithosphere, *J. geophys. Res.,* **90,** 12 623–12 632.

Grevemeyer, I., Flueh, E.R., Reichert, C., Bialas, J., Kläschen, D., Kopp, C. & Weinrebe, W., 1998. Crustal and upper mantle structure of Ninetyeast Ridge, Indian Ocean, *EOS, Trans, Am. geophys. Un.,* **79** (Fall mtg suppl.), 871–872.

Grevemeyer, I., Flueh, E.R., Reichert, C., Bialas, J., Kläschen, D. & Kopp, C., 2000. Crustal architecture and deep structure of the Ninetyeast Ridge hotspot trail from active source ocean bottom seismology, *Geophys. J. Int.,* submitted.

Hinz, K., 1981. A hypothesis on terrestrial catastrophes: wedges of very thick oceanward dipping layers beneath passive margins—their origin and paleoenvironmental significance, *Geol. Jahrb.,* **E22,** 3–28.

Ito, G. & Clift, P.D., 1998. Subsidence and growth of Pacific Cretaceous plateaus, *Earth planet. Sci. Lett.,* **161,** 85–100.

McAdoo, D.C. & Sandwell, D.T., 1989. On the source of cross-grain lineations in the central Pacific gravity field, *J. geophys. Res.,* **94,** 9341–9352.

McKenzie, D.P. & Bowin, C., 1976. The relationship between bathymetry and gravity in the Atlantic Ocean, *J. geophys. Res.,* **81,** 1903–1915.

McKenzie, D.P. & Fairhead, D., 1997. Estimates of the effective elastic thickness of the continental lithosphere from Bouguer and free air gravity anomalies, *J. geophys. Res.,* **102,** 27 523–27 552.

McNutt, M.K. & Shure, L., 1986. Estimating the compensation depth of the Hawaiian swell with linear filters, *J. geophys. Res.,* **91,** 13 915–13 923.

Morgan, W.J., 1981. Hotspot tracks and the opening of the Atlantic and Indian oceans, in *The Sea,* pp. 443–487, ed. Emiliani, C., Wiley, New York.

Mutter, J.C., Talwani, M. & Stoffa, P.L., 1982. Origin of seaward-dipping reflectors in oceanic crust off the Norwegian margin by 'subaerial seafloor spreading', *Geology,* **10,** 353–357.

National Geophysical Data Center, 1995. GEODAS/TRKDAS CD-ROM, Version 3.1, Announcement 95-MGG-02, National Oceanic Atmosphere Administration, US Dep. Com., Washington, DC.

Parson, B. & Sclater, J.G., 1977. An analysis of the variation of ocean floor bathymetry and heat flow with age, *J. geophys. Res.,* **82,** 803–828.

Peirce, J.W., 1978. The northwards motion of India since the Late Cretaceous, *Geophys. J. R. astr. Soc.,* **52,** 277–312.

Peirce, J.W. *et al.*, 1989. *Proc. ODP Init. Rep.,* **121.**

Planke, S., 1994. Geophysical response of flood basalts from analysis of wire line logs: Ocean Drilling Proram Site 642, Voring volcanic margin, *J. geophys. Res.,* **99,** 9279–9296.

Planke, S. & Eldholm, O., 1994. Seismic response and construction of seaward dipping wedges of flood basalts: Voring volcanic margin, *J. geophys. Res.,* **99,** 9263–9278.

Ribe, N.M. & Christensen, U.R., 1994. Three-dimensional modelling of plume–lithosphere interaction, *J. geophys. Res.,* **99,** 669–682.

Royer, J.-Y., Peirce, J.W. & Weissel, J.K., 1991. Tectonic constraints on the hotspot formation of Ninetyeast Ridge, *Proc. ODP Sci. Res.,* **121,** 763–776.

Sandwell, D.T. & Smith, W.H.F., 1997. Marine gravity anomaly from Geosat and ERS-1 satellite altimetry, *J. geophys. Res.,* **102,** 10 039–10 054.

Saunders, A.D., Storey, M., Gibson, I.L., Leat, P., Hergt, J. & Thompson, R.N., 1991. Chemical and isotopic constraints on the origin of basalts from Ninetyeast Ridge: results from DSDP legs 22 and 26 and ODP leg 121, *Proc. ODP Sci. Res.,* **121,** 559–584.

Sleep, N.H., 1990. Hotspots and mantle plumes: some phenomenology, *J. geophys. Res.,* **95,** 6715–6736.

Smith, W.H.F. & Sandwell, D.T., 1997. Global seafloor topography from satellite altimetry and ship soundings, *Science,* **277,** 1956–1962.

Staudigel, H. & Schmincke, H.-U., 1984. The Pliocene seamount series of La Palma, Canary Islands, *J. geophys. Res.,* **89,** 11 195–11 215.

ten Brink, U.S. & Brocher, T.M., 1987. Multichannel seismic evidence for a subcrustal complex under Oahu and a model for Hawaiian volcanism, *J. geophys. Res.,* **92,** 13 687–13 707.

Watts, A.B., 1978. An analysis of isostasy in the world's oceans, 1: Hawaii-Emperor seamount chain, *J. geophys. Res.,* **83,** 5889–6004.

Watts, A.B. & ten Brink, U.S., 1989. Crustal structure, flexure, and subsidence history of the Hawaiian islands, *J. geophys. Res.,* **94,** 10 473–10 500.

Watts, A.B., ten Brink, U.S., Buhl, P. & Brocher, T.M., 1985. A multichannel seismic study of the lithospheric flexure across the Hawaiian-Emperor seamount chain, *Nature,* **315,** 105–111.

Wessel, P. & Smith, W.H.F., 1991. Free software helps map and display data, *EOS, Trans. Am. geophys. Un.,* **72,** 441–446.

Wolfe, C.J., McNutt, M.K. & Detrick, R.S., 1994. The Marquesas archipelagic apron: seismic stratigraphy and implications for volcano growth, mass wasting, and crustal underplating, *J. geophys. Res.,* **99,** 13 591–13 608.