LETTERS
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Seafloor deformation and forecasts of the April 2011 eruption at Axial Seamount

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Axial Seamount is an active submarine volcano located at the intersection between the Cobb hotspot and the Juan de Fuca spreading centre in the northeast Pacific Ocean[1,2]. The volcano has been closely monitored since it erupted in 1998 (refs 3,4). Since then, Axial Seamount seemed to exhibit a similar inflation–deflation cycle to basaltic volcanoes on land and, on that basis, was expected to erupt again sometime before 2014 or 2020 (refs 5,6). In April 2011 Axial Seamount erupted. Here we report continuous measurements of ocean bottom pressure that document the deflation–inflation cycle of Axial Seamount between 1998 and 2011. We find that the volcano inflation rate, caused by the intrusion of magma, gradually increased in the months leading up to the 2011 eruption. Sudden uplift occurred 40–55 min before the eruption onset, which we interpret as a precursor event. Based on our measurements of ground deformation through the entire eruption cycle at Axial Seamount, we suggest that another eruption could occur as early as 2018. We propose that the long-term eruptive cycle of Axial Seamount could be more predictable compared with its subaerial counterparts because the volcano receives a relatively steady supply of magma through the Cobb hotspot and because it is located on thin oceanic crust at a spreading plate boundary.

In July 2011, during previously planned fieldwork with a remotely operated vehicle, we discovered that Axial Seamount had erupted sometime since the previous summer when we found that several long-term monitoring sites were buried by up to 4 m of new lava (Fig. 1). Our limited dive observations, combined with those from two subsequent expeditions, showed that eruptive vents for the new flows were located on the upper south rift zone, close to the source area of the previous eruption in 1998 (ref. 3). However, the volume erupted in 2011 seems to be larger because sheet lava flowed farther from the vents (>2 km) and from a greater distance along the upper south rift zone (~10 km). A quick response coordinated with colleagues at sea allowed the upper south rift zone to be resurveyed with an autonomous underwater vehicle, producing a high-resolution map of post-eruption bathymetry that reveals the 2011 lava flows in spectacular and unprecedented detail[7]. A third follow-up expedition resurveyed the entire 50-km length of Axial's south rift zone with ship-based multibeam sonar and a comparison with an earlier survey shows depth changes of up to 137 m along a 5-km long ridge located 30 km south of the caldera, probably constructed of pillow lavas erupted during the same event[7].

A start date of 6 April 2011 for this latest eruption at Axial Seamount is evident from data recorded by *in situ* monitoring instruments that were recovered in July, including two bottom pressure recorders (BPRs, described below) and two ocean bottom hydrophones[8]. This is the first seafloor eruption monitored by both *in situ* seismic and geodetic instruments and the data provide new insights into the dynamics and sequence of events.

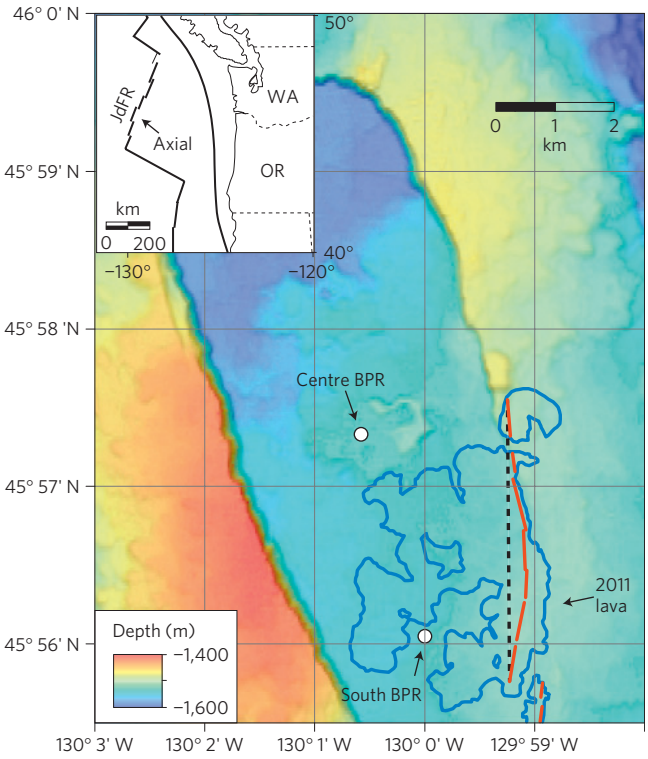

Figure 1 | Bathymetric map of the summit caldera of Axial Seamount. The locations of the two bottom pressure recorders (BPRs) that measured vertical movements of the sea floor during the 2011 eruption are shown, along with the lava flows that were erupted in April 2011 (blue outlines) and their eruptive vents (red lines), from ref. 7. The black dashed line shows the location of the model dyke (3.3 km × 2.0 km × 1.0 m) that can reproduce the pre-eruption uplift observed at the BPRs. JdFR, Juan de Fuca Ridge; WA, Washington; OR, Oregon.

Ground movements measured at active volcanoes can be used to model the location and geometry of shallow magma reservoirs and the dynamics of subsurface magma movements. At subaerial

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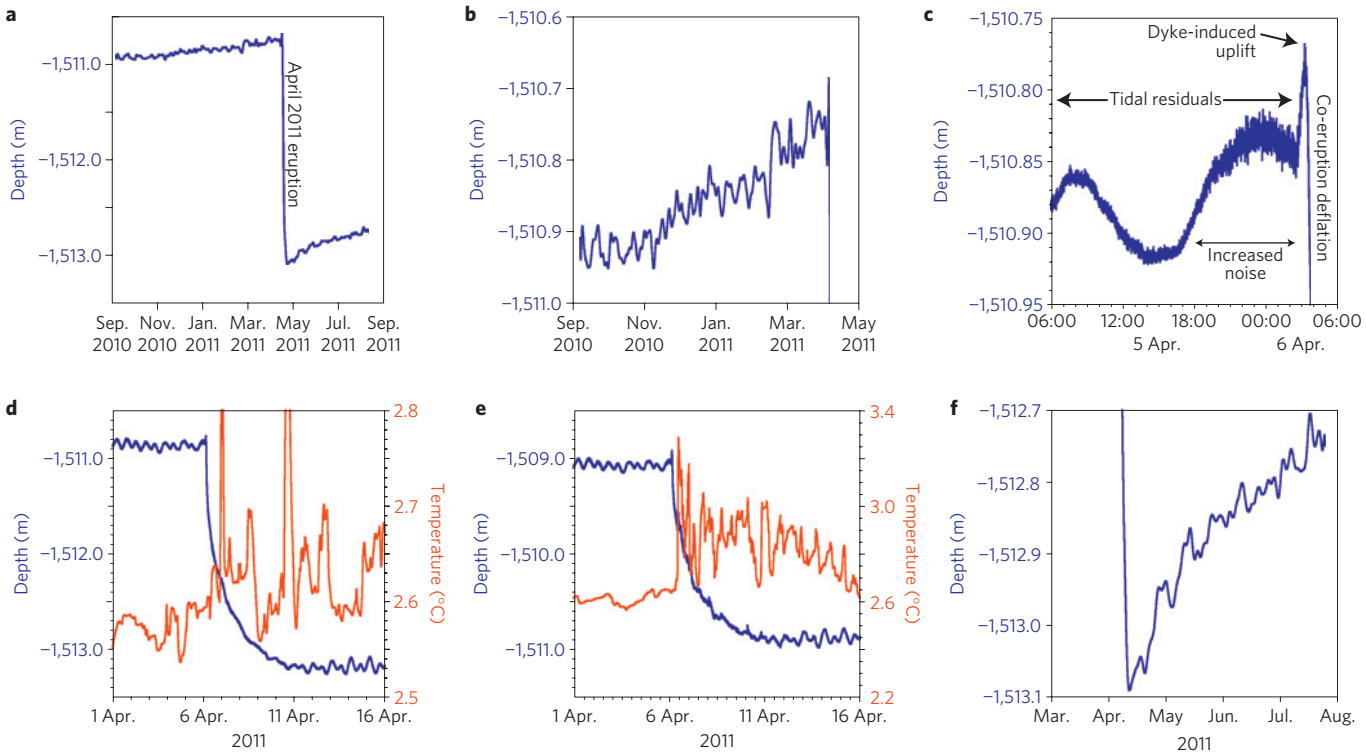

Figure 2 | BPR data from the 2011 eruption. a, Entire year-long, drift-corrected record from the center BPR, showing sudden deflation of −2.4 m at the time of the 2011 eruption. **b**, Pre-eruption increase in inflation rate at centre BPR before the 2011 eruption. **c**, Detail near the eruption onset showing increased noise in the centre BPR, dyke-induced uplift and abrupt change to rapid deflation. **d**, Co-eruption deflation at an exponentially decreasing rate (blue) and temperature (red) recorded inside the centre-BPR pressure case. **e**, Co-eruption deflation (blue) and temperature (red) at the south BPR. **f**, Post-eruption re-inflation at an exponentially decreasing rate recorded by the centre BPR. **a**, **b** and **f** are low-pass filtered to remove tides and show long-term trends; **c**, **d** and **e** have a tide model[26] subtracted to retain high-frequency information.

basaltic volcanoes, repetitive cycles of deformation are common, characterized by long periods of gradual inflation as magma accumulates in a shallow reservoir, separated by sudden brief deflation events when magma leaves the reservoir and is intruded into rift zones or erupted[9,10]. At Axial Seamount, precise pressure measurements have been used to measure vertical movements of the sea floor in two ways. Continuously recording BPRs have been deployed for one or more years at a time and can detect large sudden uplifts or deflation events[11]. However, BPRs cannot independently measure long-term gradual volcanic inflation between eruptions (typically at rates of 10–20 cm yr^{-1}), because they may have an inherent linear drift at about the same rate[12]. Therefore, beginning in 2000, we developed another method to measure long-term inflation at Axial Seamount using a mobile pressure recorder (MPR) connected to a remotely operated vehicle to make relative depth measurements every 1–3 years at an array of seafloor benchmarks inside the summit caldera relative to a reference site located 10 km away[5,6]. The MPR measurements can also be used to constrain the drift rate of co-located BPRs. The data from the centre BPR (Fig. 1) is drift-corrected in this way below. Drift- and tide-corrected BPR data uncertainty varies from about $\sigma \approx 2.3$ cm for measurements longer than a tidal cycle to about $\sigma \approx 0.5$ cm for shorter-duration signals owing to unmodelled oceanographic signals and background noise levels, where σ is the standard deviation.

The year-long centre-BPR record is characterized by pre-eruption inflation, a large co-eruption deflation and post-eruption re-inflation (Fig. 2a). These data show that the rate of inflation gradually increased in the months leading up to the 2011 eruption (Fig. 2b). The last pre-eruption MPR survey in September 2010 measured 49.4 ± 0.6 cm (all uncertainties given are 1σ) of uplift at the caldera centre since the previous survey in August 2007 (16 ± 0.4 cm yr^{-1}), about the same as the average rate of inflation from 2000 to 2010 (15 ± 0.2 cm yr^{-1}), indicating that the rate had been close to linear during the past decade. However, the centre-BPR data show the average inflation rate increased to 34 ± 0.5 cm yr^{-1} from September 2010 to the eruption and to 50 ± 0.5 cm yr^{-1} during the first three months of 2011 (Fig. 2b).

Both BPRs recorded short-term precursors before the onset of the main deflation. About 8 h before deflation began (~18:30 on 5 April 2011, all times Greenwich Mean Time), the amplitude of high-frequency noise in both BPR records doubled (Fig. 2c). Then at 02:30 on 6 April, a sudden uplift began simultaneously at both BPRs, amounting to 7 ± 0.9 cm in 40 min at the centre BPR (Fig. 2c) and 13 ± 1.1 cm in 55 min at the south BPR. We interpret that this uplift was caused by a dyke intruding to the surface from the shallow magma reservoir[13,14], because a model rectangular dyke with 1.0 m of uniform opening in an elastic half-space[15,16] reaching the surface at the 2011 eruptive fissures (Fig. 1) would produce the uplift observed at the BPRs.

We interpret that the eruption of lava started when the dyke-induced uplift ended and the large deflation began. Temperatures recorded inside the BPR pressure cases support this interpretation, because they rose soon after the onset of deflation, probably owing to lava flowing on the sea floor nearby. The temperature at the centre BPR rose by 0.2 °C 18 h after the onset of deflation (Fig. 2d) and at the south BPR the temperature increased by 0.6 °C 6.5 h after deflation started (Fig. 2e). The time lags are apparently owing to how much time it took for lava to flow from the eruptive vents to the BPRs, indicating flow advance rates of 100–200 m h^{-1}. The differences in the time lag and temperature increase are consistent with their distance from the eruptive vents and how close the

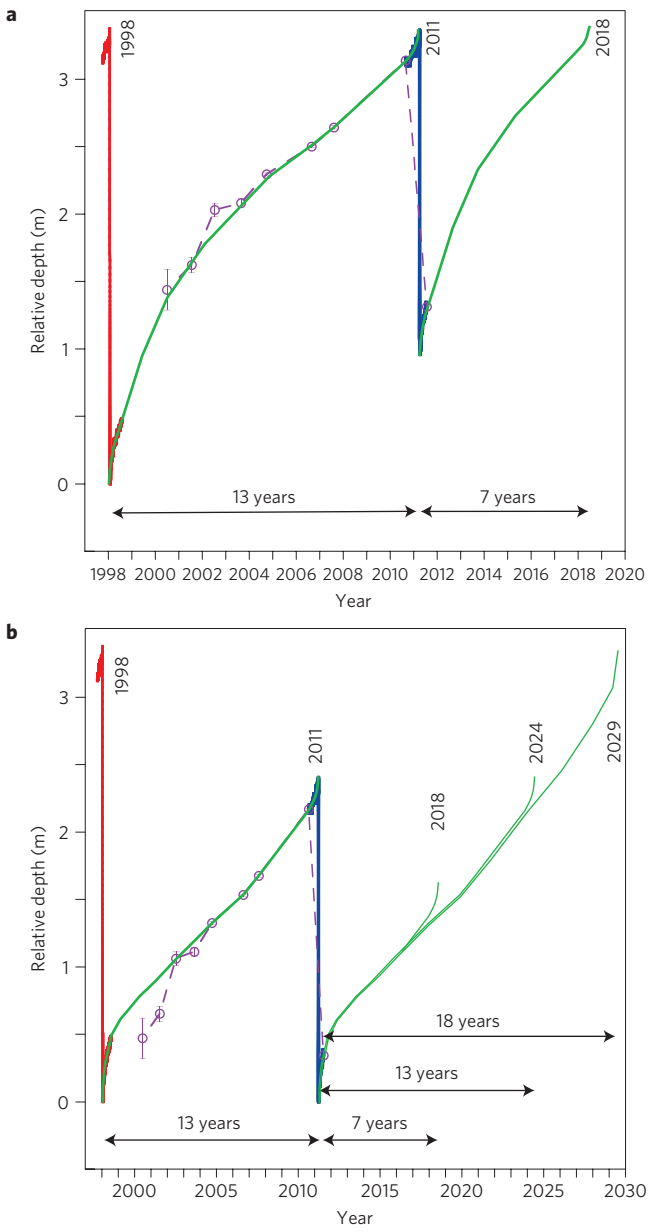

Figure 3 | Two forecast scenarios for the next eruption at Axial Seamount, based on the cycle of inflation and deflation. In both, the intereruption MPR data (purple dots, error bars as in ref. 6) are coregistered with the 2011 centre BPR data (blue), but their exact relationship (in relative depth) to the 1998 BPR data (red) is unknown. **a**, Time-predictable model in which eruptions (deflations) are triggered at a critical level of inflation and the next eruption at Axial would be expected in 2018. **b**, Volume-predictable model in which the volume of the next eruption is predictable based on the time since the last one, but the date it will occur is unknown.

lava got to the instruments. The centre BPR is 1,750 m from the eruptive vents and 540 m from the nearest lava, whereas the south BPR is 1,100 m from the eruptive vents and lava reached within 125 m (Fig. 1).

The large deflation event began at 03:10 on 6 April 2011 at the centre BPR, but at 03:25 at the south BPR. We interpret that the dyke-induced uplift recorded by the south BPR lasted longer because the dyke first reached the surface at the north end of the eruptive vents (adjacent to the centre BPR) and propagated southward, reaching the surface 15 min later adjacent to the south BPR. This would imply a lateral propagation rate of 0.27 m s^{-1}, similar to the rate of 0.23 m s^{-1} documented during Axial's 1998 eruption by earthquake epicentres advancing down the south rift zone[17].

The main deflation lasted ~6 days and amounted to -2.43 ± 0.02 m of subsidence at the centre BPR (Fig. 2d) and -1.98 ± 0.03 m at the south BPR (Fig. 2e). The subsidence rate was initially as high as 50 cm h^{-1} and decreased exponentially until about 12 April. This subsidence was caused by magma leaving the shallow reservoir and intruding down the south rift zone and erupting at the surface[9,18]. Thus, the duration of subsidence is also the duration of the intrusion and eruption. The lack of other deflation events in the BPR records also implies that there were no other periods of eruption. In fact, as soon as the deflation ended, re-inflation started at a high rate that decreased exponentially with time until the BPRs were recovered (Fig. 2f). The post-eruption uplift amounted to 35 ± 0.7 cm in 3.5 months, or an average rate of more than 1.2 m yr^{-1}.

Interestingly, the duration of deflation during the 1998 and 2011 eruptions was the same (~6 days), although the magnitude of subsidence was greater in 1998 (−3.2 m; ref. 11) than in 2011 (−2.4 m). This implies that a smaller volume of magma was removed from the summit reservoir in 2011 than in 1998, even though the volume of lava erupted in 2011 (ref. 7) was larger than in 1998 (ref. 3). This discrepancy is probably because the 2011 dyke intrusion was smaller in volume than in 1998. This interpretation is supported by the fact that in 1998, T-wave epicentres migrated 50 km down the south rift zone[17], indicating the length of that dyke, even though there was no evidence of lava eruption beyond 10 km south of the caldera[3]. In 2011, the regional hydroacoustic monitoring system was disabled and no epicentre migration could be detected[8], but lava was apparently erupted 30 km south of the caldera[7]. During the 1998 eruption, a volume of 207×10^6 m^3 was estimated to have been removed from the summit magma reservoir, assuming a point-source elastic deformation source[19] at a depth of 3.8 km beneath the centre of the caldera[20,21]. Of that volume, $100–150 \times 10^6$ m^3 was in the dyke that intruded down the south rift zone, assuming a length of 50 km, a height of 2–3 km and a thickness of 1 m. Using the same methods, a volume of 147×10^6 m^3 was removed from the summit reservoir during the 2011 eruption. In this case, the volume of lava erupted is well constrained to be 99×10^6 m^3 by bathymetric remapping[7]. If the dyke that intruded down the south rift had the same thickness (1 m) and height (2–3 km), but a length of 33 km, then the dyke volume would be $66–99 \times 10^6$ m^3. Slight reductions in the thickness or height parameters would make the sum of the 2011 dyke and lava volumes consistent with the calculated deflation volume.

After 1998, attempts were made to forecast Axial's next eruption, based on the simple assumption that the volcano would be ready to erupt again when it had re-inflated to the pre-1998 level. However, a gap in monitoring between 1998 and 2000 created a fundamental ambiguity about how the post-1998 eruption re-inflation had evolved. Chadwick *et al.*[5] stated that the next eruption would occur before 2014, whereas Nooner and Chadwick[6] made a more conservative forecast of before 2020 because of the uncertainties in the time series. Even though these published forecasts had eruption windows of years, they were nevertheless proved correct and represent the first successful eruption forecast at a submarine volcano.

Now with the first documented eruption cycle at Axial, we look ahead and attempt to forecast the next event, but still with the ambiguity owing to the 1998–2000 data gap. If we assume that the cycle is time-predictable and the 1998 and 2011 eruptions both occurred at the same level of inflation, the next eruption would be expected in 2018 (Fig. 3a). This would be 7 years between eruptions, shorter than the 13-year recurrence interval between 1998 and 2011, because the deflation in 2011 was smaller than in 1998.

The other end-member possibility is that the pattern is volume-predictable. In this case, the timing of the next eruption would not be predictable, but the volume of magma removed from the summit reservoir would be, based on the time since the last eruption. For example, an eruption in 7 years would be smaller in volume than the last two, an eruption equal in size to 2011 could recur in 13 years, but one the size of the 1998 eruption would not occur until 2029 (Fig. 3b).

We hypothesize that the pattern at Axial may be more predictable than at volcanoes on land, as its location at a spreading centre means that the underlying crust is thin and it probably has a more direct, steady and simple magma supply system[2,13,14]. The short-lived increased rate of re-inflation after an eruption has been modelled as poroelastic and/or viscoelastic relaxation in the upper crust[6] superimposed on a linear rate of background magma supply from greater depth. The increased rate of inflation leading up to the 2011 eruption has not been seen before at Axial and we speculate that it may be the result of magma leakage or a staged ascent from the shallow magma reservoir leading to pressure decrease and vesiculation, a process that may ultimately trigger eruptions[22–24]. We will be able to test these hypotheses by continuing geodetic monitoring at Axial, particularly once a regional cabled observatory is established as part of the Ocean Observatories Initiative[25].

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Author contributions

W.W.C. and S.L.N. contributed equally to this work. W.W.C. wrote the manuscript. D.A.B. and M.D.L. were co-principal investigators on the expedition that discovered the 2011 eruption at Axial Seamount.

Additional information

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