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A Sea-Floor Spreading Event Captured by Seismometers

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Two-thirds of Earth's surface is formed at mid-ocean ridges, yet sea-floor spreading events are poorly understood because they occur far beneath the ocean surface. At 9°50'N on the East Pacific Rise, ocean-bottom seismometers recently recorded the microearthquake character of a mid-ocean ridge eruption, including precursory activity. A gradual ramp-up in activity rates since seismic monitoring began at this site in October 2003 suggests that eruptions may be forecast in the fast-spreading environment. The pattern culminates in an intense but brief (~6-hour) inferred diking event on 22 January 2006, followed by rapid tapering to markedly decreased levels of seismicity.

The ocean floor is episodically created by injections of magma in dikes that commonly erupt along divergent boundaries that separate tectonic plates. The timing and mechanics of these sea-floor spreading events must normally be inferred from remote seismic or hydroacoustic data and from sea-floor geology. Along fast-spreading ridges, most on-axis seismicity is too small in local magnitude (<2 M_L) to be recorded by global seismic networks or regional hydrophone arrays (*1*). A long-standing goal of mid-ocean ridge (MOR) research has been to capture the seismic precursors, signature, and aftermath of a sea-floor spreading event and eruption within a network of ocean-bottom seismometers (OBSs).

The East Pacific Rise (EPR) near 9°50'N spreads at a full rate of ~110 mm year^{-1} (*2*) and is one of the best-studied MOR segments in the world. Ever since an eruption was documented in 1991 (*3*, *4*), scientists have regularly returned to document ecosystem progression (*5*, *6*), to study changes in vent-fluid chemistry and temperature (*7*, *8*), and to conduct detailed geological mapping (*9*). Based on the predicted decadal-scale repeat rate of eruptions at the northern EPR (*10*), we initiated a 3-year OBS monitoring program in October 2003 as part of the National Science Foundation's Ridge2000 Program of coordinated research at this integrated study site (*11*). Since then, an array of up to 12 OBSs has been deployed in an ~4-by-4–km area between 9°49'N and 9°51'N, with approximately annual data recovery (Fig. 1).

The OBSs, which are deployed from a ship, each contain a seismometer that records the velocity of ground motion, a data-recording package, and an acoustic transponder that allows basic communication with the surface, including instrument release. The release system, when triggered by a coded acoustic pulse, separates the instrument from its anchor, allowing it to rise to the surface for recovery.

In the fast-spreading ridge environment, upper-crust microseismicity is dominated by small cracking events. This activity is driven largely by hydrothermal cooling (*12*) as well as stress concentrations associated with the shallow (1430 meters below the sea floor) axial magma chamber (*13*). The upper crust is therefore sensitive to crustal inflation and/or heating, as well as to increasing extensional stresses. A clear trend of increasing seismicity (*14*) from tens to many hundreds of events per day from October 2003 to May 2005 (Fig. 2) was thus interpreted as reflecting conditions within the system that were building toward an eruption (*15*). The average daily seismicity rate in 1995 was ~2.7 events per day, detected between 9°49'N and 9°51'N with a similarly designed array of nine OBSs (*12*). This activity is about one to two orders of magnitude lower than that observed from 2003 to 2006, indicating substantial differences on multiyear-to-decadal time scales, through different phases of the volcanic/tectonic cycle.

On 25 April 2006, during an expedition of the research vessel (R/V) *Knorr* to service the array, only 4 of 12 instruments were recovered (Fig. 1). Five OBSs were silent, and three were acknowledging anchor-release commands but not leaving the sea floor. In the context of the preceding years' seismicity and a pattern of instrument loss nearest the axial summit trough (AST), an eruption was immediately suspected to have occurred since the last OBS servicing in May 2005.

Corroborating evidence for this theory came from anomalies in water-column measurements of temperature and light scattering made from R/V *Knorr*. During a subsequent R/V *New Horizon* cruise (May 2006), an along-axis conductivity-temperature-depth (CTD)–optical and sample-bottle rosette tow confirmed ex-

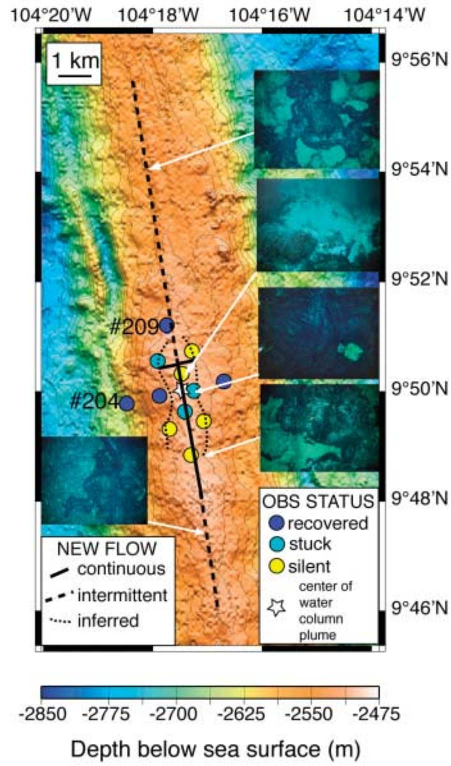

Fig. 1. Map of the EPR 9°50'N area (*26*) showing the OBS locations and estimated extent of the new flow. Insets are TowCam photographs showing contact relationships of the new lava flows and OBS no. 210 stuck in lava (images ~4 to 6 m across). In some locations, the on-axis new flow is continuous [e.g., 9°48'N to 9°50.5'N (solid black line)], whereas further north and south there are 50- to 200-m-long sections where it is discontinuous.

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ceptionally high light attenuation (Δc) values ($>0.15\ m^{-1}$) (Fig. 3), indicative of vigorous discharge of high-temperature hydrothermal fluids. Maximum Δc was centered precisely over the OBS array during both cruises, with density-inversion layers found throughout the bottom-most 100 m, especially between 9°48.5′N and 9°50.5′N. Their magnitude, variability, and near ubiquity over this area, along with exceptionally high methane concentrations, are symptomatic of a sea floor that discharges hot, potentially low-chlorinity, hydrothermal fluid. These qualities also suggest that an eruption had occurred less than 7 months before May 2006 (*14*).

Sea-floor images collected using a digital towed camera system [TowCam (*16*)] confirmed the existence of new lavas and constrained the eruption's spatial extent (Fig. 1). The new lavas appear to be erupted from fissures within the AST, which reestablished quickly after the event by drain-back and collapse. Comparison of TowCam bathymetry with pre-eruption Alvin mapping (*17*) suggests that the AST is now 10 to 15 m narrower and a few meters shallower at 9°50.4′N than it was previously. Lava flow morphologies indicate that the highest effusion rates were near 9°50′N (*18*).

Radiometric dating (*14*) of 10 rocks collected from the young terrain is under way, using ^{210}Po (*4*). Preliminary ^{210}Po results indicate that nine of the rocks were erupted within a year before their collection, with dates ranging from late summer 2005 to January 2006.

Based on the sea-floor images, the extent of water column anomalies, the preliminary lava ages, and the distribution of OBSs that failed to return, we estimate that the flow extended intermittently for ≥18 km along the ridge axis, from 9°46′N to 9°55.7′N, with off-axis extent ranging from 0 to ≥1 km. The eruption occurred on the same segment (segment B) as the 1991 to 1992 eruption, with a similar length scale.

Data from only two of the four OBSs recovered in 2006 are presently available because of hard-drive problems, but efforts are being made to recover these data and more OBSs (*14*). The available data come from the northernmost instrument (no. 209), ~0.15 km west of the AST at 9°51′N, and the westernmost instrument (no. 204), ~1.8 km west of the AST near 9°50′N (Fig. 1). Automatic phase picks (Fig. 2), combined with visual inspection of the seismograms, provide a picture of year-long high earthquake rates and abundant harmonic tremors visible at a range of frequencies, particularly in the 5- to 25-Hz band. Periods of pronounced harmonic tremors reduce the signal-to-noise ratio, making automatic detection of earthquakes a less reliable indicator of large swarm activity. To better quantify the variation of seismic activity over time, we summed the root mean square (RMS) amplitude of the seismic vertical channel in the 3- to 18-Hz band within 10-min windows (Fig. 4). High-amplitude events observed on only one instrument may indicate the presence of swarms to the north or south of the array or very close to that instrument. The event on 22 January is clearly the largest event at either station and is well correlated between instruments, indicating local activity over a spatial scale important to both sensors.

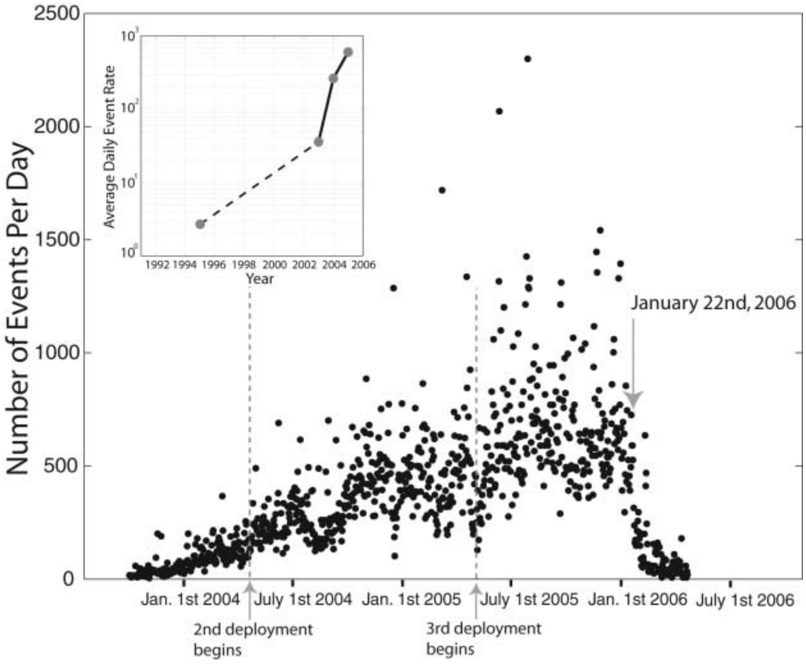

Fig. 2. Plot of the event rate from 3 October 2003 to 23 April 2006. Array turnarounds in April 2004 and May 2005 are marked with vertical dotted lines. Different methods were used to estimate event rates for the various deployments (*14*). Results were normalized by comparing periods of array overlap. The inset plot shows the average daily event rates by year, including data from a 1995 deployment (*12*).

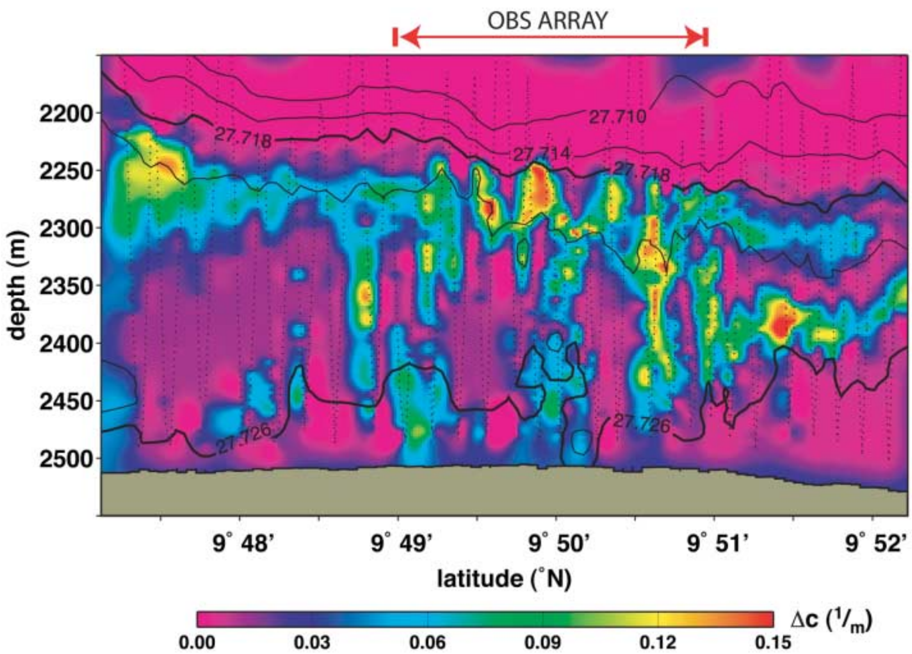

Fig. 3. Contour plot of Δc versus depth and latitude for an along-axis (ridge summit) tow-yo cast. Δc intensity is represented by colors. Potential density (sigma-theta; in kg m^{-3}) contours (solid black lines) are superimposed over Δc. The dotted line indicates the saw-toothed tow pattern of the CTD-transmissometer-bottle rosette instrument package. The deepest density line indicates localized areas of instability in the lower part of the water column; the strong correlation between the vertical structures in Δc and the deep density contour line suggest that strong localized hydrothermal venting is driving the entrainment and subsequent rise of ambient bottom water.

Seismograms and spectrograms from 22 January clearly show exceptionally high-amplitude seismic signals starting around 1345 (GMT) and continuing at high intensity for ~6 hours. Substantial earthquake activity lasted more than a week thereafter. The initial 6 hours were-dominated by strong harmonic tremors and a single-station earthquake event rate often exceeding 250 events per hour [compared with single-station rates of ~1.6 events per hour reported after the 1991 eruption (*19*)]. Both OBSs exhibit tremors at similar but not identical frequencies, indicating differences in the character of the resonator proximal to 9°51'N (no. 209) and 9°50'N (no. 204). We interpret this period of most-intense activity, associated with the major spike in the seismic RMS amplitude (Fig. 4B), as propagation of the primary dike that fed this eruption. Plume distributions and high lava effusion rates inferred from lava morphology imply a dike that originated near 9°50′N. This is consistent with 80 secondary wave–minus–primary wave measurements of the largest earthquakes (*14*), which indicate that the events were concentrated near 9°50.5′N before and during the first hour of the 6-hour period, and then were dispersed throughout the 9°49.2'N to 9°50.5′N region for the remaining ~5+ hours. This supports the idea that individual eruptions occur at the fourth-order segment scale, defined by local axial discontinuities, even though volcanic systems may be organized at the third-order scale, defined by discontinuities with off-axis expressions (*20*, *3*, *21*, *22*).

At ~1445 (GMT), seismic amplitudes peaked at about five times higher than during the rest of the 6-hour high-intensity interval (Fig. 4B). This hour-long peak may coincide with the dike rising to the surface from the axial magma chamber depth of 1.43 km (*13*), implying a vertical propagation rate of ~1.4 km hour^{-1}, consistent with typical dike propagation rates at MORs (*23*). Thus, the vertical propagation of the crack may have been preceded by ~1 hour of precursory cracking and/or magma injection at depth, manifested by lower-amplitude but intense tremor and earthquake activity. Over the weeks after the inferred diking event, tremor and seismic activity tapered rapidly to background levels substantially lower than those in the preceding months. However, brief pulses of activity were evident through April 2006.

Swarms of tremor and seismicity were observed during the preceding months as far back as May 2005 (Fig. 4A), when the last Alvin dives were conducted in this region (confirming an eruption at 9°50'N had not yet occurred). It is possible that periods of high activity may have been associated with either local minor intrusive diking/eruptive events or events north or south of the 9°50'N area, consistent with preliminary radiometric dating evidence for a mid-2005 eruption at the southern end of the flow, observed contact relationships within the new flow, and evidence that the 1991-to-1992 eruptive activity lasted ~1 year (*4*). However, it is evident in the seismic data that the primary diking event in the immediate 9°50'N area began on 22 January 2006, consistent with the relative strength of the water-column signal and the stage of ecosystem recovery (*14*). Records from three recording temperature probes (*8*) deployed in high-temperature vents at the site also provide evidence that substantial changes occurred in the hydrothermal system in the January 2006 time frame (*24*).

This event documents a known MOR eruption surface being paved over by lava from a repeat eruption, thereby completing an ~15-year full volcanic cycle that has been scrutinized by regular multidisciplinary monitoring. Our documentation of how seismic activity builds up before an eruption may make it possible to forecast future eruptions a year or more in advance. The brevity and intensity of the culminating dike event suggest rapid tapping of the axial magma chamber as compared with slower-spreading ridges (*23*, *25*). A 6-hour window for the primary diking event emphasizes the need for multidisciplinary in situ monitoring to fully characterize the geological, chemical, and biological phenomena associated with this fundamental process that shapes our planet.

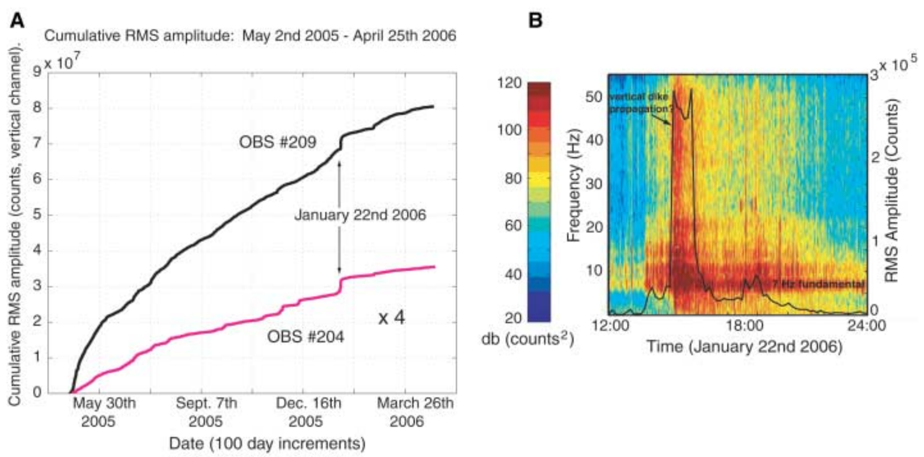

Fig. 4. (**A**) Cumulative plot of RMS amplitude of the waveforms. OBS no. 204 is multiplied by 4 to assist comparison with OBS no. 209. (**B**) Spectrogram of seismic data from 1200 to 2400 on 22 January 2006 from no. 209, showing the most intense activity of the year interpreted as the propagation of a dike from depth. The black line shows the RMS amplitude from Fig. 4A, which provides a quantitative measure of signal strength. db, decibels.

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