

Anatomy of a seafloor spreading event captured by in situ seismogeodesy

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Over geological time, the growth of the ocean floor involves magmatic and tectonic extension¹ at mid-ocean ridges (MORs). Because seismogeodetic monitoring of these submarine plate boundaries remains challenging^{2–7}, little is known about how these systems operate on yearly timescales. Here we report the first, to our knowledge, in situ observation of a rifting event at a MOR segment that combines hydroacoustic, direct-path ranging and bottom-pressure measurements, with repeated seafloor mapping. This event started on 26 April 2024 at the axis of the Southeast Indian Ridge (SEIR) near 37° S, two months after instruments had been deployed across the ridge axis and nearby Amsterdam transform fault (TF). The event began as a rapidly migrating swarm of extensional seismicity along the axial valley. It caused 4 m of subsidence of the valley floor and more than a metre of horizontal extension across the valley. We interpret this as the deflation of a sill-like reservoir feeding propagating dykes along the ridge axis. The dykes eventually led to the outpouring of about 160 million m³ of lava at the seafloor in about 16 days, while inducing both seismic and aseismic slip on valley-bounding normal faults and finally triggering seismic activity on the abutting TFs. Large-scale aseismic slip induced by magmatic processes could therefore be the primary mechanism by which MOR normal faults accrue their displacement, which would account for their well-documented seismic deficit^{8,9}.

Two-thirds of Earth's surface was created along the 65,000-km-long MOR system, a network of narrow tectonic boundaries in which new lithospheric plates form and drift apart at a scale of centimetres per year. Under MORs, mantle rises and partially melts on decompressing. Buoyant magma ascends towards the ridge axis, where it crystallizes as new oceanic crust within spreading segments bounded by TFs or non-transform offsets. Magmatic emplacement, however, rarely accounts for all of the plate divergence and part of the extension is accommodated by slip on normal faults of all sizes¹. Over hundreds of thousands of years, this interplay of magmatic and tectonic deformation shapes abyssal hills, which cover most of the ocean floor^{10,11}. Little is known, however, on how these processes unfold on short timescales. Seafloor spreading is thought to proceed as a succession of 'quantum' events of extension, involving earthquakes and dyke intrusions¹². These events can last several hours to several months and recur on decadal timescales, depending on the local spreading rate and magma supply. Many questions remain about how stresses accumulate between these events^{13,14}, the degree to which activity on spreading segments and nearby TFs is synchronized¹⁵ and why MORs release so little seismic energy given their rapid time-averaged deformation rates^{8,9}. These knowledge gaps originate from the challenge of simultaneously and continuously monitoring, for several years, the low-level seismic activity and the horizontal and vertical displacements of the seafloor along submarine plate boundaries^{16,17}. We took on this challenge by installing

an autonomous seismogeodetic observatory on an active MOR segment and its abutting TF and were lucky enough to capture a notable seafloor spreading event two months into our experiment.

Setting of the OHA-GEODAMS experiment

The OHA-GEODAMS (Observatory with Hydro-Acoustics and Geodesy near Amsterdam Island) observatory was deployed late February 2024 across the axis of the SEIR at 37° 07' S (segment I1 (refs. 18,19)) and across the nearby Amsterdam TF (Fig. 1a). This region marks the northernmost extent of the Saint Paul–Amsterdam volcanic plateau, which the SEIR is now splitting apart^{18–20}. The local spreading rate is 61 mm year^{−1} based on magnetic anomalies^{21,22} and 63 mm year^{−1} according to space geodesy²³. The seafloor produced at segment I1 is typical of intermediate-spreading MORs, with an approximately 2,000-m-deep axial valley flanked by fault-bounded abyssal hills, hundreds of metres tall and spaced roughly every 2 km (Fig. 1b). This area experiences one to two Mw ≥ 5 earthquakes each year either on the Amsterdam TF or the Boomerang TF that bound segment I1 and has the advantage of being regularly visited by R/V Marion Dufresne on her yearly voyages to maintain the French scientific research stations in the Southern Indian Ocean islands.

Our observatory comprises an array of five autonomous hydrophones, encompassing the whole Saint Paul–Amsterdam plateau (Fig. 1a), to

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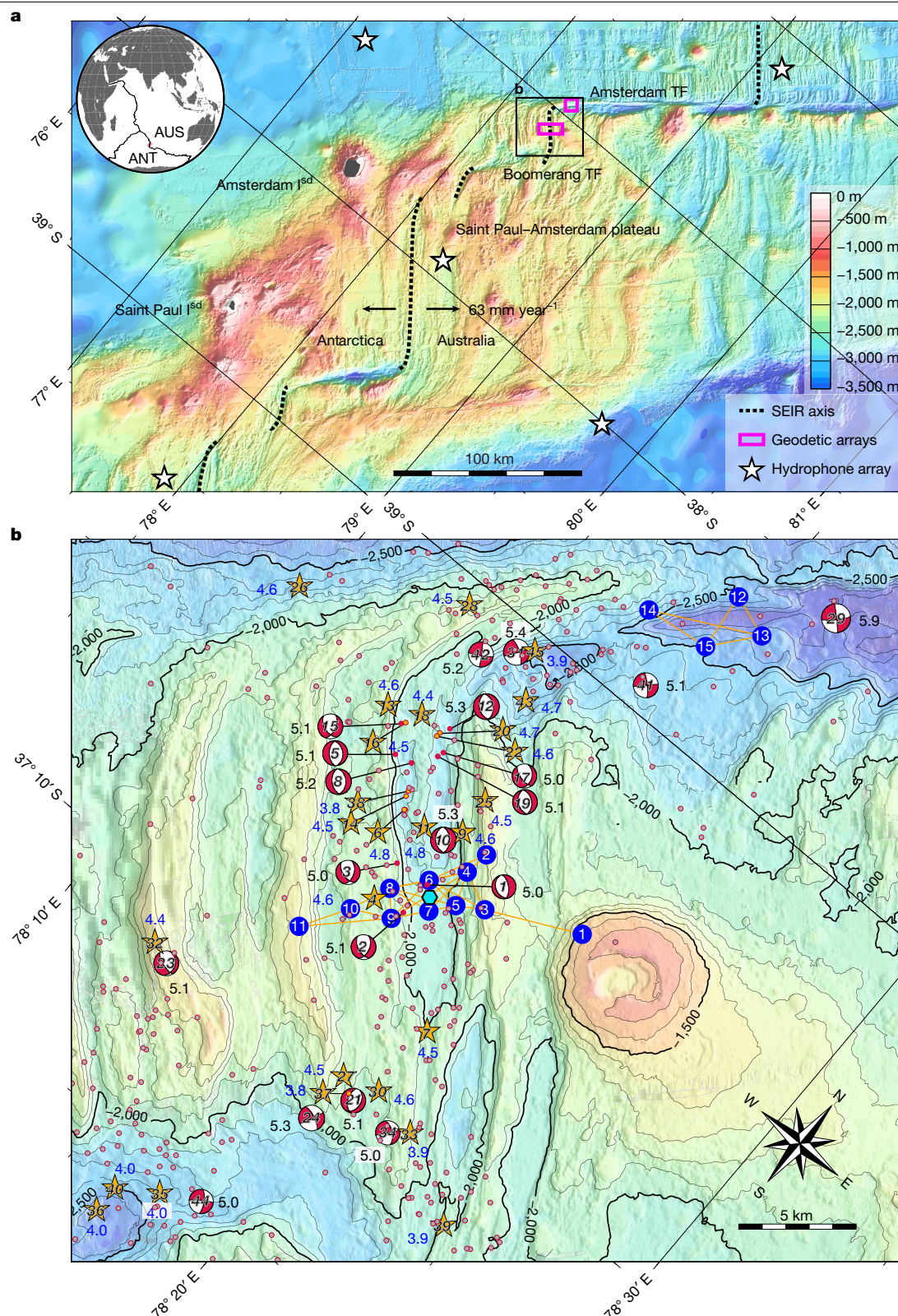


Fig. 1 | Tectonic setting and seismicity of the captured seafloor spreading and transform faulting event. **a**, This event occurred along the SEIR segment II (in the black rectangle), located on the Saint Paul-Amsterdam plateau in the Southern Indian Ocean (oblique Mercator projection). The seismogeodetic experiment included a wide array of autonomous hydrophones (stars), two arrays of acoustic ranging beacons and one BPR (in the purple rectangles) and repeated swath-bathymetry surveys of the axial valley and its intersection with the two abutting TFs. **b**, Earthquake crisis of 26 and 27 April 2024. GCMT focal mechanisms (red with Mw magnitudes in black) and ISC events (orange stars

with mb magnitudes in blue) from land-based catalogues are numbered sequentially (italicized numbers; Extended Data Table 1) and were all relocated from the recordings of the hydrophone array, which also recorded many lower-magnitude hydroacoustic events (grey dots). Horizontal displacements were measured along direct-path ranging baselines (orange lines) between acoustic beacons (white numbers in blue circles) distributed in two arrays. Vertical displacement in the axial valley floor was measured with a self-calibrating BPR (cyan hexagon).

monitor the regional seismic activity. Passive acoustics (Methods) have proved to be very effective in locating low-magnitude seismic activity in MOR contexts, with a location accuracy of 1–2 km or better and completeness on the order of $m_b = 3.9$ (refs. 15, 24–26). They have been particularly successful at detecting seafloor spreading events involving dyke injection and eruption^{27–30}. To monitor horizontal displacements at the ridge–transform intersection, we deployed 15 acoustic-ranging beacons or transponders (TP (refs. 3, 7, 31)) on the seafloor (Fig. 1b), 11 straddling the axial valley (TP1–TP11) and four across the Amsterdam TF (TP12–TP15). To make baselines as long as possible, the beacons were mounted on high tripods and placed on ridge crests and cliff edges. Across the axial valley, beacons were set along two parallel lines, 1.3 km apart with common end-stations, to extend the lateral coverage of the array and to ensure redundancy in case of instrument failure. Overall, the network spans 11 km, with baselines ranging in length from 1,100 to 4,300 m. Owing to the rugged and elevated terrain, not all beacons can communicate with all of their neighbours; still, a total of 32 baselines can be monitored by direct-path ranging. The TF array forms a diamond spanning the Amsterdam TF, with four 1,940–4,940-m-long baselines. Ranging measurements were repeated every 4 h in the ridge array and every 2 h in the TF array to measure the relative displacements between transponders (Methods). Finally, we deployed a drift-controlled bottom-pressure recorder (BPR) between transponders TP6 and TP7 (Fig. 1b) to monitor vertical displacements of the axial valley floor (Methods). Even though all of these approaches have been used previously to study ground deformation associated with seafloor spreading^{2–7}, this is the first time that they have all been implemented simultaneously on a MOR segment and abutting TF exhibiting substantial tectonic activity.

Seismicity and seafloor displacements

On 26 April 2024, at 19:56 UTC, a notable swarm of extensional seismicity began in the middle of segment I1 with five small events detected by the hydrophones, followed by a Global Centroid Moment Tensor (GCMT)³² $M_w = 4.9$ normal-faulting earthquake at 20:09, located under the axial valley (number 1 in Fig. 1b). This initial seismic activity, with a subsequent $M_w = 5.1$ and 16 lower-magnitude earthquakes, migrated more than 8 km towards the southeastern end of the axial valley until 20:35 (Fig. 2a). It was followed minutes later by a series of seven $M_w \geq 5$ normal-faulting (GCMT), eight $4.8 > m_b > 4.4$ (International Seismological Centre (ISC))³³ and four lower-magnitude earthquakes, which migrated more than 9 km from the segment centre to its northwestern end, in the direction opposite to that of the initial migration phase. Such migrating patterns are typical signatures of dyke propagation events along extensional plate boundaries^{34–36}, although the migration rates involved in this case ($2–3 \text{ m s}^{-1}$, from the regressions shown in Fig. 2a) are an order of magnitude faster than those documented in analogous, albeit longer, sequences (Table 1 in ref. 29). Remarkably, the axial valley floor is 200 m shallower and narrower at the southeastern end of the segment compared with its northwestern end (Fig. 1b). A southeastward dyke intrusion from the segment centre may thus have been hindered by topographic stresses³⁷, giving way to a more mechanically favourable northwestward intrusion.

In the meantime, the BPR in the axial valley floor recorded a series of discrete subsidence events, that is, sudden pressure increases amounting to between 1.7 and 3.3 cm of vertical motion coincident with each of the first large normal-faulting events (Fig. 2a). Using the rupture size inferred from the GCMT magnitude³⁸ and fault dips given by the focal mechanisms, we find that these earthquakes, modelled as circular ruptures in an elastic half-space (Methods), could not have occurred any deeper than about 5 km below the seafloor to cause the observed coseismic subsidence (Extended Data Fig. 1). These markedly shallow depths are in strong contrast to those estimated by the GCMT catalogue (12–16 km below the seafloor), probably because of the poor teleseismic coverage of the area.

Subsidence of the axial valley floor accelerated after a $M_w = 5.1$ event at 21:03 (number 5 in Fig. 1b), in a stepwise manner, averaging about 5 cm min^{-1} while the putative dyke propagated to the northwest. When the propagation stopped at about 21:40, cumulative seafloor subsidence had reached 1.2 m (Fig. 2a). Subsidence then slowed abruptly and continued at a lesser rate of about 0.6 cm min^{-1} until 01:30 on 27 April (Fig. 2b). It slowed further to 1.2 cm day^{-1} until 00:00 on 3 May and beyond (Extended Data Fig. 2). The total subsidence amounted to 4.2 m over a period of 6 days, of which 83% occurred in the first 16 h. This is almost twice the total subsidence of 2.45 m measured over 12 days during the 2015 eruption of Axial Seamount, of which 91% occurred during the first 24 h (ref. 17). Like at Axial Seamount, we interpret this vertical displacement of the valley floor as resulting from the drainage of an underlying magma reservoir (for example, axial melt lens³⁹). The rapid subsidence between 21:03 and 21:40 may specifically represent the drainage from the magma reservoir into a northwest-propagating dyke. Rising near-bottom water temperature recorded by the BPR suggests that lava may have reached the seafloor as early as 22:00 (Fig. 2 and Extended Data Fig. 2). Past that time, slower seafloor subsidence may reflect magma drainage through open fractures connecting the reservoir to the seafloor.

Nearly concurrently, the direct-path acoustic ranging array straddling the axial valley recorded substantial horizontal displacements (Fig. 3). During the February 2025 maintenance cruise, given the challenge to reposition the beacons on the seafloor, only the central station TP7 was recovered to access its full dataset. Baselines remained fairly constant until the ranging session at 21:12 on 26 April, which nearly coincided with the $M_w = 5.2$ normal-faulting event at 21:09 (number 8 in Fig. 1b), at the beginning of the rapid subsidence phase of the BPR. Afterwards, baselines markedly changed but fluctuated about their new lengths, probably because of rapid changes in sound speed induced by fluctuating ambient temperatures (Fig. 2b). The temperature field was then certainly not uniform near the axial valley floor (that is, around TP7) and affected all acoustic travel times to the elevated beacons on the valley walls. Nevertheless, by averaging the ranging measurements before the ambient temperature increased by more than about 0.1°C , baselines from station TP7 to the two stations located on top of the southwest valley wall (TP8 and TP9) clearly lengthened by up to 1.30 m, whereas, on the opposite side of the valley, baselines shortened by 0.53 m (TP4 and TP5) and 0.86 m (TP3; averaging windows shown in Fig. 3). These displacements are one order of magnitude larger than those measured across the Juan de Fuca Ridge at 46°N during the 25 January 1998 dyke intrusion at Axial Seamount^{4,31}. However, our baselines do not show any obvious extension related to some inflation before the 26 April events, as was observed at Axial Seamount. All tripods tilted by several degrees during the swarm of nearby $M_w \geq 5$ quakes. Because we cannot tell in which direction they tilted, the uncertainties in the baseline changes include the worst-case scenario (that is, acoustic heads fully tilting apart or closer). Extension between TP8–TP9 and TP7 continued until June 2024 and reached up to +1.80 m, whereas TP3–TP4–TP5 ended up closer to TP7 by -0.64 to -0.86 m (Extended Data Fig. 3). Notably, baseline TP6–TP7 also diminished. This could be because of the subsidence of the two transponders, as recorded by the built-in pressure gauge in TP7 (Extended Data Fig. 2c), possibly suggesting that the deflation of the magma reservoir was centred below the BPR and TP7 (Fig. 3), which both subsided by about 4 m.

The initial displacements (Fig. 3) along a cross-axis line joining TP9 to TP3, through TP7 and TP5, provide critical constraints to evaluate the interplay of different tectonomagmatic deformation sources during the early stages of the spreading event, that is, fault slip, deflation of a magma reservoir and intrusion of a dyke. Station TP7 subsided by $3.75 \text{ m} \pm 0.55 \text{ m}$, whereas TP9 moved away from TP7 and TP5 and TP3 moved closer to TP7. Such massive subsidence is readily explained by a deflating magmatic sill⁴⁰ that would also induce horizontal

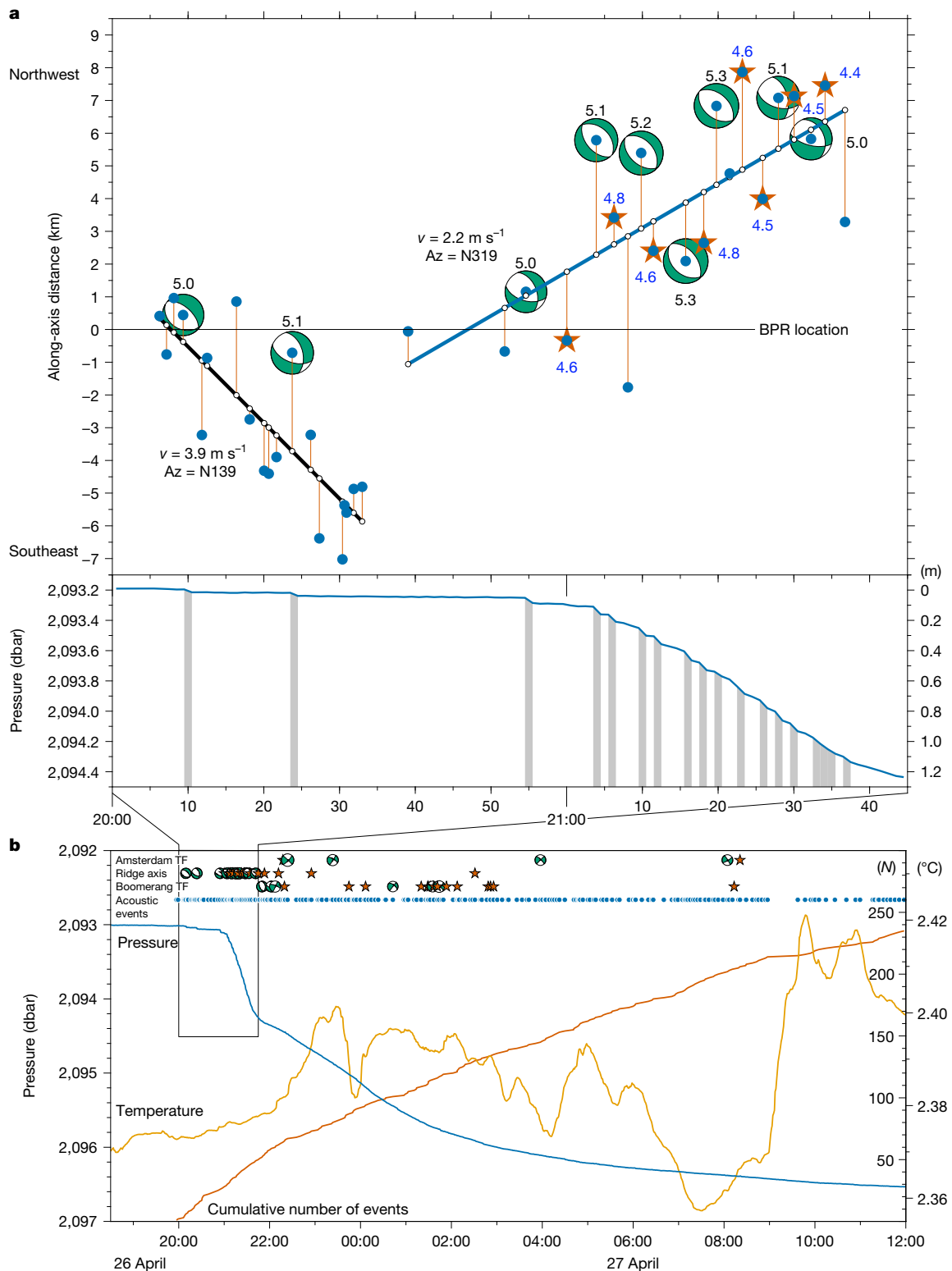


Fig. 2 | Initial sequence of seismic events and vertical displacements of the valley floor. **a**, Sequence of events in the axial valley interpreted as the result of dyke propagations, initially to the southeast (N139) and then to the northwest (N319), at an average speed of about 3 m s^{-1} . Along-axis distances are relative to the BPR location. GCMT focal mechanisms (green), ISC (orange stars) and hydroacoustic events (blue dots) are shown with their Mw (black) and mb (blue) magnitudes, respectively. The lower part shows the BPR recordings of the coseismic subsidence of the valley floor as the dyke propagated; episodes of

subsidence exceeding 1.7 cm min^{-1} are shaded. Map view of the events and dyke propagations is shown in Extended Data Fig. 9. **b**, Longer-term subsidence (blue curve, $1 \text{ dbar} \approx 1 \text{ m}$) and temperature changes (orange curve) recorded by the BPR in the axial valley floor. The framed area corresponds to the time window in panel **a**. The brown curve is the cumulative number (N) of seismic and hydroacoustic events reported at the top of the panel and distributed between the axial valley and the two adjacent TFs.

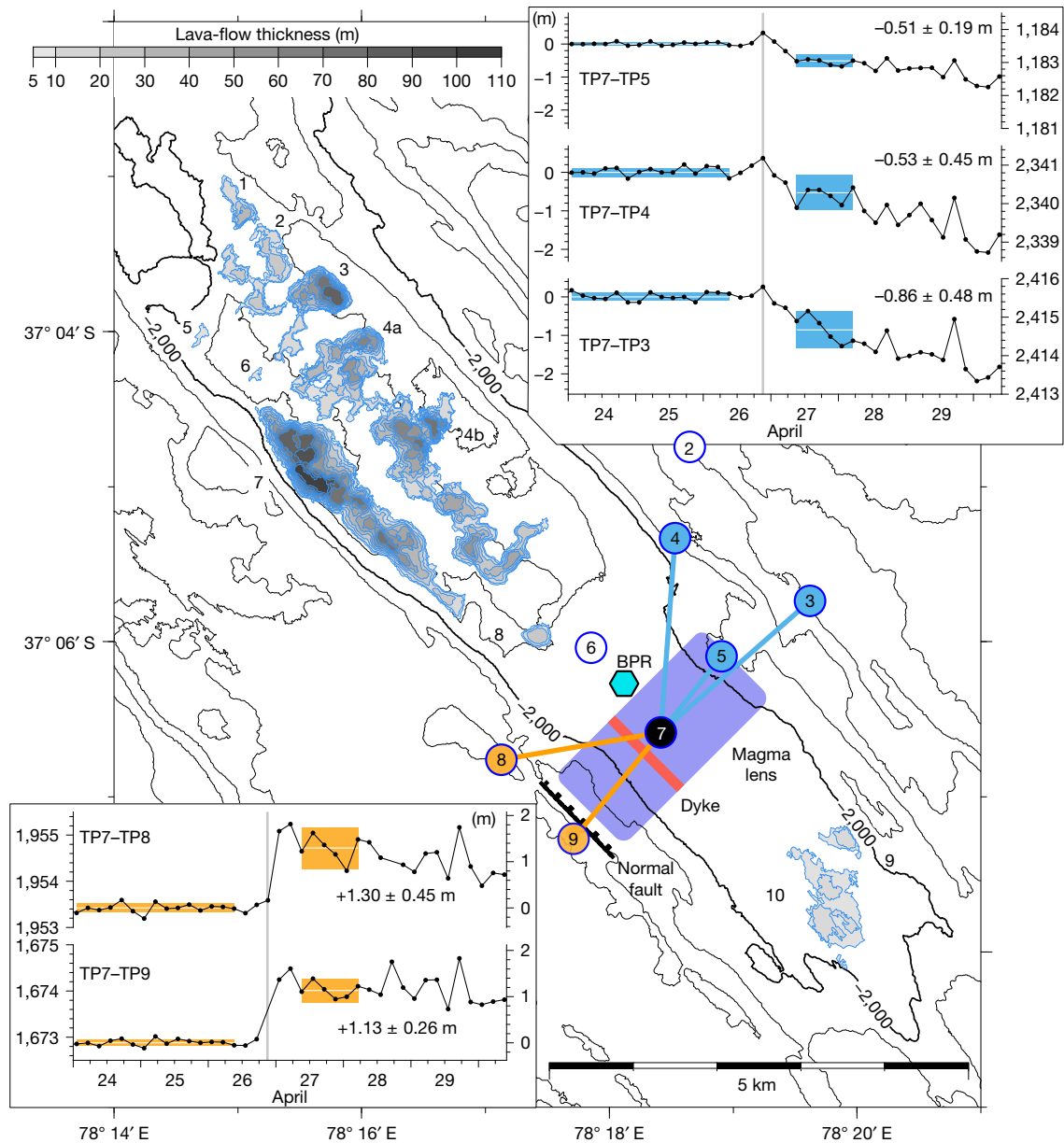


Fig. 3 | Initial baseline changes in the axial valley, and extent and thickness of the new lava flows. Displacements in metres are measured from transponder TP7 along the coloured baselines to the other transponders (numbered circles), which are either lengthening (orange) or shortening (blue). Greyed patches with 10-m contours in light blue show the extent of the new lava flows, which exceed a thickness of 90 m in places (see greyscale in the upper left); volumes of patches 1 to 10 are given in Extended Data Fig. 6). Insets show the initial changes in the baselines with up to 1.30 m extension to the southwest

(TP8, TP9) and 0.86 m contraction to the northeast (TP3, TP4, TP5). Coloured rectangles show averaging windows and 1σ uncertainty. The vertical grey line corresponds to the time of the rapid subsidence of the BPR (between 21:00 and 21:40 on 26 April; Fig. 2b). The baseline changes are interpreted as the combined result of a propagating dyke and a deflating magma lens at depth below TP7 (purple rectangle) and normal slip along a fault bordering the axial valley and dipping 60° inwards towards the dyke (Fig. 4). Longer-term changes in the baselines are shown in Extended Data Fig. 3.

contraction bringing all transponders closer to TP7 (Extended Data Fig. 4). Lengthening of the baselines thus requires sources of extension between TP9 and TP7, such as the opening of a dyke and/or slip on a normal fault.

Using 2D elastic dislocation models (Methods), we randomly sampled 10 million combinations of sill, dyke and fault geometries to assess how well they could account for the observed displacements (Extended Data Fig. 5). Of these, 2,203 yielded a satisfactory root mean square (RMS) misfit (<20 cm). They have in common: (1) a sill at least 3,500 m deep collapsing by 12–18 m; (2) a dyke rooted at the sill, extending to sub-seafloor depths of 83–377 m and opening by 1.0–3.3 m; (3) 0.6–3.1 m of slip on a normal fault down to a few kilometres; and

(4) a total horizontal extension of 2.1–4.0 m, distributed between the dyke and the fault. Most models favour the dyke taking up more extension than the fault. As an illustration, Fig. 4 presents a plausible model with a sill, 2,500 m wide and 3,600 m deep, deflated by 9.8 m; a dyke rising to 57 m depth beneath the geodetic network and opening by 1.4 m; a northeast-dipping axial-valley bounding fault slipping by 1.9 m down to 1,500 m depth. Such a large amount of slip, one order of magnitude larger than expected from any $M_w \approx 5$ earthquakes of the swarm (Methods), implies that the fault motion largely occurred aseismically. In this particular scenario, the total horizontal extension amounts to 2.4 m (60% dyke, 40% fault), which is equivalent to 38 years of spreading at 63 mm year^{-1} .

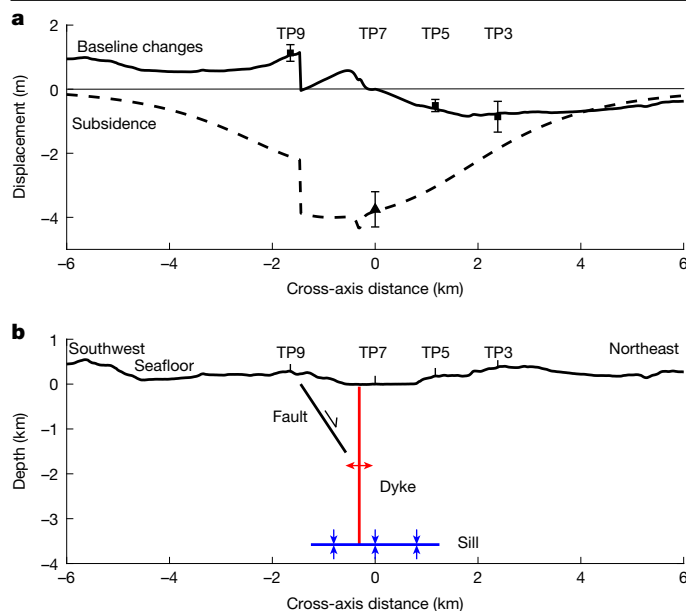


Fig. 4 | Example of a 2D deformation model fitting the observed vertical displacements and baseline changes relative to TP7 along a profile perpendicular to the axial valley. **a**, Overall baseline changes (ΔL ; Methods; continuous line) and vertical subsidence (dashed line). The overall horizontal displacement is 2.4 m (60% dyke, 40% fault). **b**, Geometry of the model components below a bathymetric cross-section: a 3,577-m-deep sill deflating by 9.8 m, a 1.4-m-wide dyke rising 3,520 m from the sill up to 57 m below seafloor, between TP9 and TP7 (310 m southwest of TP7) and 1.9 m of slip down to 1,526 m depth on a northeast-dipping normal fault (total RMS misfit = 17 cm). A schematic map view of the sill, dyke and fault is shown in Fig. 3. The individual contribution of each component—sill, dyke and fault—to the displacements is shown in Extended Data Fig. 4. This is one of the 2,203 solutions best fitting the data (RMS misfit < 20 cm) out of 10 million randomly sampled models. The only fixed parameters were the fault dip set at 60°, based on focal mechanisms, the fault location along a southwest valley wall between TP7 and TP9 and the sill width across axis set at 2,500 m and centred on TP7 (Methods). Coloured arrows show the expected type of motion on the fault, dyke and sill.

New lava flows on the seafloor

During the deployment of the observatory (2024) and first maintenance cruise (2025), we repeated a ship-based swath-bathymetry mapping of the axial valley, its flanks and its connection with the Amsterdam TF. To compensate for the lack of high-resolution mapping near the seabed, we collected several overlapping swaths at reduced speed during each leg. Subtracting the digital terrain models (DTMs)^{41,42} from the 2024 and 2025 surveys revealed marked changes in valley-floor topography (Fig. 3), despite the low resolution (20 m) of the models with depth-sounding uncertainties up to 5 m. Relative to 2024, the 2025 survey mapped large areas with positive depth changes, locally exceeding 90 m. We interpreted these areas as the outlines of substantial new lava flows along two distinct parallel lines. The thickest one, forming a 4-km-long patch (number 7 in Fig. 3), outpoured at the foot of the southwestern valley wall, which experienced several large normal-faulting events. The second line of massive lava flows forms a series of distinct or connected patches (numbered from 1 to 4) aligned with the axial volcanic high that was mapped along the ridge axis in 2024. A 40-m-tall circular patch (number 8) formed only 600 m away from beacon TP6. The northwest-propagating dyke probably fed the central line of lava flows but also supplied magma that possibly extruded through the western fault plane. Two other patches (numbers 9 and 10, with thicknesses up to 20 m) are located at the southeastern end of the segment and were probably fed by the early southeast-propagating dyke. The total volume of new lavas ranges from 148 to 160 million m³

(Extended Data Fig. 6), in the range of lava emplacements reported in comparable MOR contexts (for example, the Galápagos, Gorda, Juan de Fuca ridges; Fig. 12 in ref. 43).

The timing of lava effusion can be constrained through indirect evidence: (1) the change of slope in the rapid subsidence phase of the BPR, which coincides with a gradual increase of the sea-bottom temperature starting on 26 April at 22:00 (Fig. 2b and Extended Data Fig. 2) and (2) the occurrence of numerous short (<10 s) and energetic hydroacoustic events, called H-waves and generated in the water column by lava–seawater interactions^{16,44–47} (Extended Data Fig. 2). These events begin around 06:00 on 27 April. There may have been earlier ones, masked by the intense seismic activity recorded by the hydrophones (Extended Data Fig. 7). H-wave events greatly increased after 27 April. More than 2,150 were recorded by at least three hydrophones by 12 May, after which they stopped, suggesting that the eruption lasted only 16 days, thus with an average rate of 9–10 million m³ of lava extrusion per day (effusive rate of 116 m³ s^{−1}) and a final short outburst on 15 and 16 June 2024. The three main pulses of H-wave events match increases in the sea-bottom temperature at the BPR (Extended Data Fig. 2). Their sources cluster around the northern lava flows, which are also the most voluminous. At Axial Seamount and the East Pacific Rise, the occurrence of these impulsive events were similarly interpreted as marking the onset and duration of lava extrusion^{16,44,45}.

Transform activation and strain budget

Shortly after the dyke stopped propagating northward (21:40 on 26 April), seismic activity started in the area of the Boomerang TF with unexpected off-axis normal-faulting events (numbers 21 and 23 in Fig. 1b), with fault planes oblique relative to the strike of the axial valley, as well as strike-slip events (number 24 in Fig. 1b). Twenty minutes later (at 22:23), the Amsterdam TF produced several strike-slip earthquakes, including a notable Mw = 5.9 event (number 29 in Fig. 1b). This intense activity resulted in substantial tilts among the transponder array straddling the TF. Together with large cyclical changes in the sound speed, this tilting hindered our ability to detect any resolvable change in the length of baselines (Extended Data Fig. 3b). Overall, the seismicity timeline (Fig. 2b) strongly suggests that the rupture of the Boomerang TF, followed by that of the Amsterdam TF, was triggered by the dyke propagation along the adjacent ridge axis. A similar causal relationship was inferred following the 2006 eruption at the East Pacific Rise at 9° 50' N (ref. 15). Estimation of Coulomb stress changes (Methods) imparted by a dyke on strike-slip receiver faults representative of the Boomerang and Amsterdam TFs supports this hypothesis (Extended Data Fig. 8). Altogether, the transform seismicity triggered by the 2024 seafloor spreading event amounts to about 12 PJ km^{−1} of seismic moment release on the Amsterdam TF and about 3 PJ km^{−1} along the Boomerang TF (1 PJ = 10¹⁵ J). These values are not unusual compared with earlier bursts of moment release, which have been occurring regularly on these two TFs for several decades, as recorded by the GCMT catalogue³² (Fig. 5).

By contrast, the approximately 25-km-long II spreading segment released no detectable normal-faulting moment before 2017. Between 2017 and 2023, it released about 14 PJ km^{−1} and the 2024 migrating swarm events (Extended Data Fig. 9) accounts for an extra approximately 22.6 PJ km^{−1}. Notably, about 98% of the elastic models that fit our geodetic observations involve a normal-faulting moment larger than 22.6 PJ km^{−1} (brown histogram in Extended Data Fig. 5c). The median normal-faulting moment of these models is 92.3 PJ km^{−1} (range 29.1–212.9 PJ km^{−1}, corresponding to the 16th and 84th percentiles, capturing 68% of the probability mass). By definition, this 'geodetic' moment includes both a seismic and an aseismic component, which, given our median estimate, implies that fault slip during the 2024 event was about 24% seismic and about 76% aseismic. This demonstrates the ability of MOR normal faults to experience aseismic slip events, which

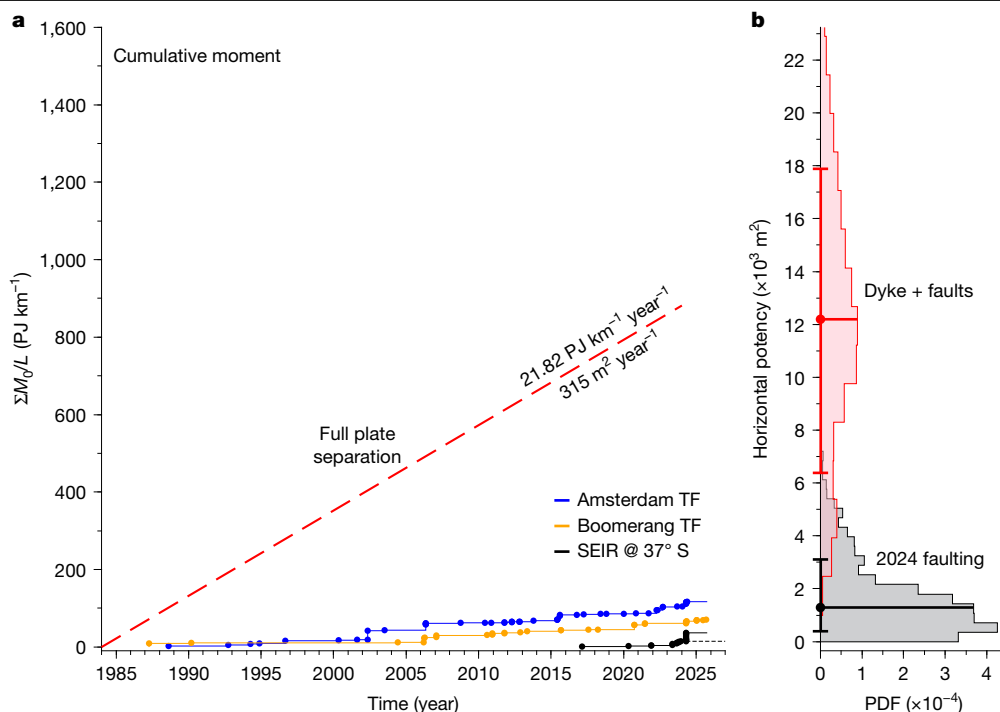


Fig. 5 | Cumulative moment budget along the Amsterdam and Boomerang TFs and spreading segment in between (37° 05' S, segment II) based on the GCMT catalogue³² and horizontal potency⁴⁸ of the 2024 spreading event.

a, Seismic moments (M_0), expressed in 10^{15} J or PJ, have been normalized by the length (L) of the TFs and ridge segment: 115, 54 and 25 km, respectively. The dashed line indicates the expected horizontal potency rate (and its equivalent moment rate for a fault dipping at 60°) for a ridge segment continuously spreading at 6.3 cm year^{-1} . **b**, Probability density function (PDF) of the equivalent horizontal potency⁴⁸ released by fault slip—seismic and aseismic (grey histogram; modelled in Extended Data Fig. 5c); relative to the median

normal-faulting moment (black symbol with range corresponding to the 16th and 84th percentiles), it shows that the 2024 event was about 24% seismic and about 76% aseismic. The same quantity can be estimated for the dyke as the product of its opening by its height (Extended Data Fig. 5d,e). These distributions can be combined to estimate the total horizontal potency of the 2024 spreading event (tectonic + magmatic; red histogram); the median estimate of $12.3 \times 10^3 \text{ m}^2$ (red symbol $\approx 850 \text{ PJ km}^{-1}$) would correspond to the geometric moment accumulated over about 39 years of divergence of the SEIR at 6.3 cm year^{-1} .

partly explains the well-documented deficit of extensional earthquakes in these settings^{8,9}.

Another main contributor to this deficit is the fact that MOR normal faults only accommodate a fraction $(1 - M)^{11}$ of the total plate divergence over geological time. Our results now show how this phenomenon manifests itself on a decadal timescale. Extending a 5-km-thick lithosphere at 63 mm year^{-1} amounts to a horizontal geometric moment rate of $315 \text{ m}^2 \text{ year}^{-1}$ per metre (that is, $\text{m}^2 \text{ year}^{-1}$) along axis. The geometric moment, also known as potency⁴⁸, is a kinematic quantity that, unlike the scalar moment, allows for the direct inclusion of the contribution from dykes and faults. Our median estimate for the horizontal potency released by fault slip (seismic + aseismic) during the 2024 event, assuming a dip of 60° , is $1.3 \times 10^3 \text{ m}^2$. The same quantity can be estimated for the dyke, as the product of its opening by its height (Extended Data Fig. 5d,e), yielding a median estimate of $10 \times 10^3 \text{ m}^2$. Combining these distributions yields the total horizontal potency of the 2024 spreading event (tectonic + magmatic), with a median estimate of $12.3 \times 10^3 \text{ m}^2$ (range $6.4\text{--}17.9 \times 10^3 \text{ m}^2$; red histogram in Fig. 5). This amounts to the geometric moment accumulated during 39 years (range 20–57 years) of divergence at the SEIR.

We conclude that spreading segments undergo decades of quiescent stretching as abutting transforms accrue displacements by frequent slip events. The stresses that build up in the MOR segment are released during quantum events of seafloor spreading that involve both dyking and fault slip, including notable aseismic slip on axis-bounding normal faults, akin to a caldera collapse event, such as the Kilauea's 2018 collapse⁴⁹. This may be the primary mechanism by which MOR normal

faults accumulate displacement, potentially explaining their seismic moment deficit in global catalogues⁸.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at <https://doi.org/10.1038/s41586-026-10785-0>.

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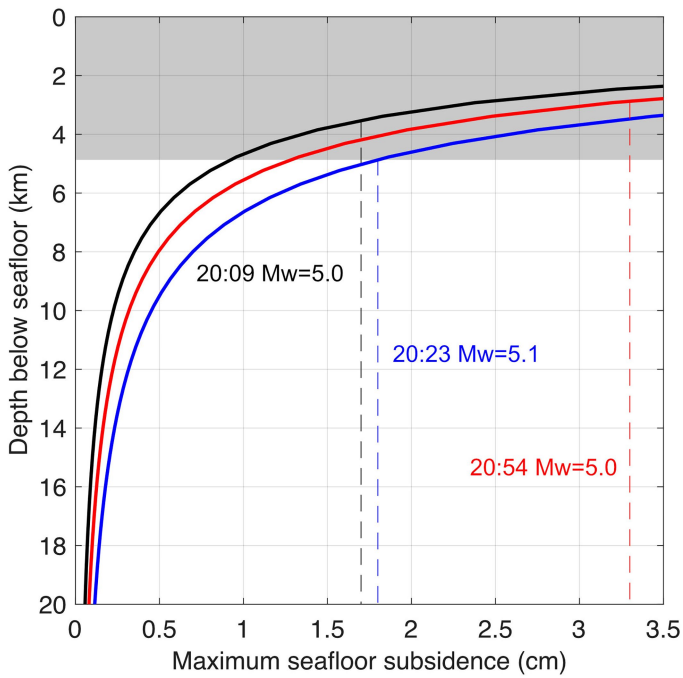
Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41586-026-10785-0>.

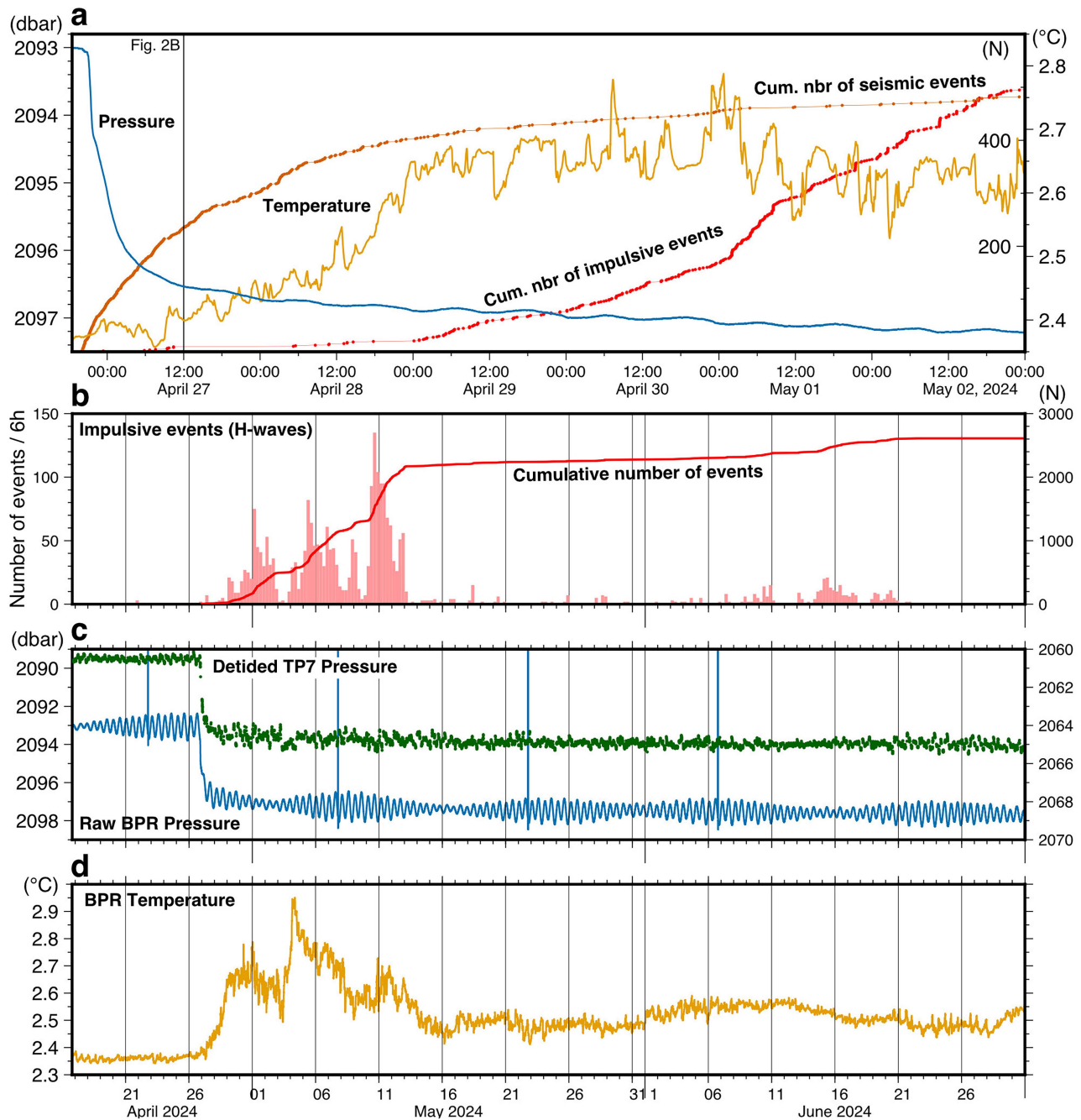
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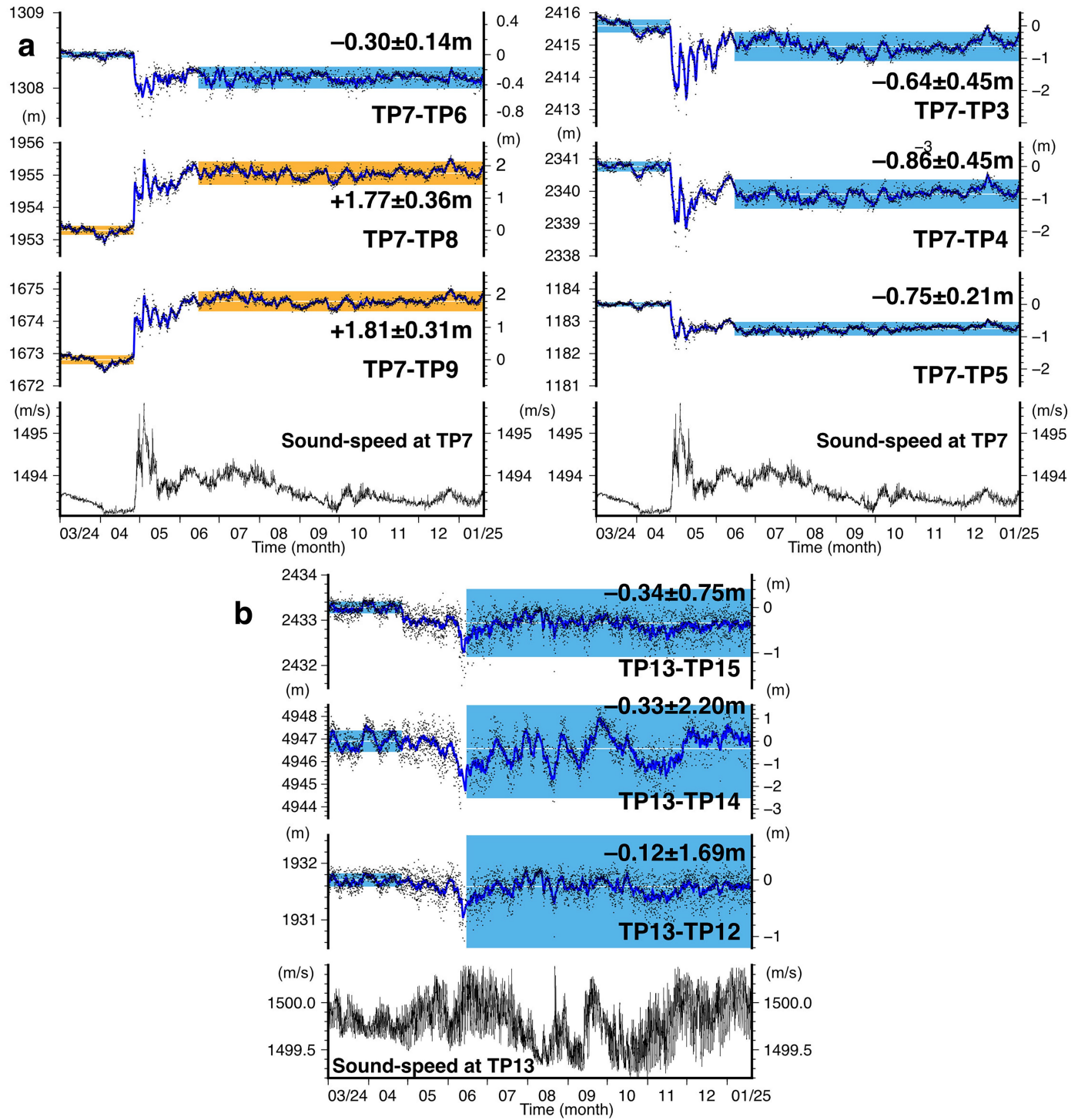


Extended Data Fig. 1 | Constraint on the depth of the first three $M_w \approx 5$ events from coseismic seafloor subsidence. Depths below the seafloor cannot exceed about 5 km (greyed area), as inferred from the rupture size (derived from M_w) and the coseismic subsidence (Fig. 2a) recorded by the BPR in the axial valley (cyan hexagon in Fig. 1).



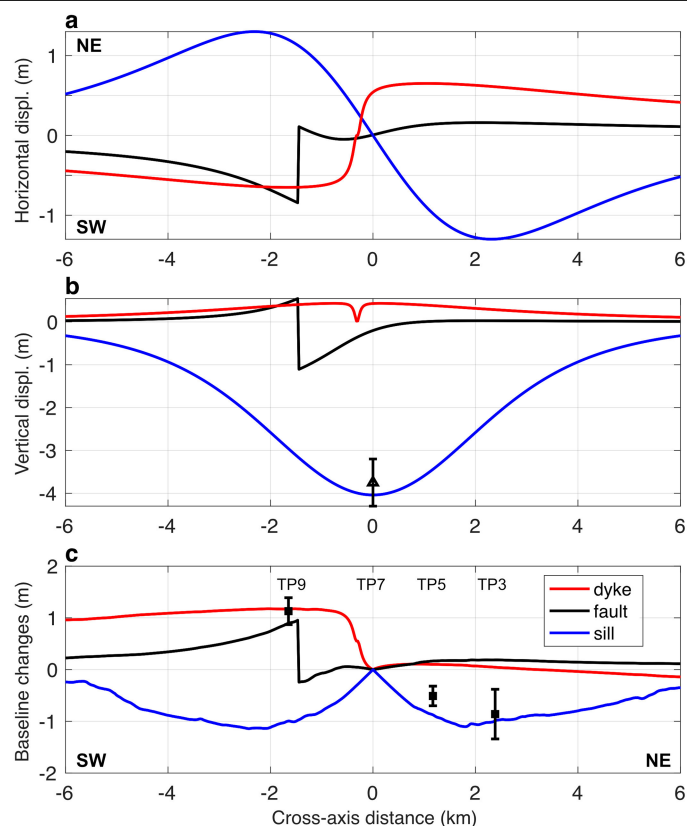
Extended Data Fig. 2 | Longer-term records of the drift-controlled bottom pressure, temperature and impulsive events. a, Pressure (blue) and temperature (orange) recorded by the BPR versus cumulative number (N) of seismic events (brown) and impulsive events (red) recorded by four hydrophones. Note the residual tide signal in the 4.2-m-high recorded subsidence (that is, 4.2 dbar pressure increase) and the gradual increase of the sea-bottom water temperature as the number of impulsive H-wave events reflecting hot lava–seawater interaction increases. **b**, Histogram (6-h bins) and cumulative number of the impulsive events (H-waves) marking the onset and

demise of the lava extrusion. They occurred in three main pulses between 26 April and 12 May 2024, with a minor burst on 15 and 16 June 2024. These events have been automatically picked on three to four hydrophones and associated for trilateration. **c**, Longer-term raw BPR pressure data (blue, left axis) showing the cyclical tide and the self-calibrating measurements (vertical bars; Methods) and pressure measured at the TP7 beacon corrected for the tide (green, right axis). TP7 and the BPR, 690 m apart (Fig. 3), both subsided by more than 4 m. **d**, Long-lasting temperature (orange) anomalies recorded near the sea bottom by the BPR.

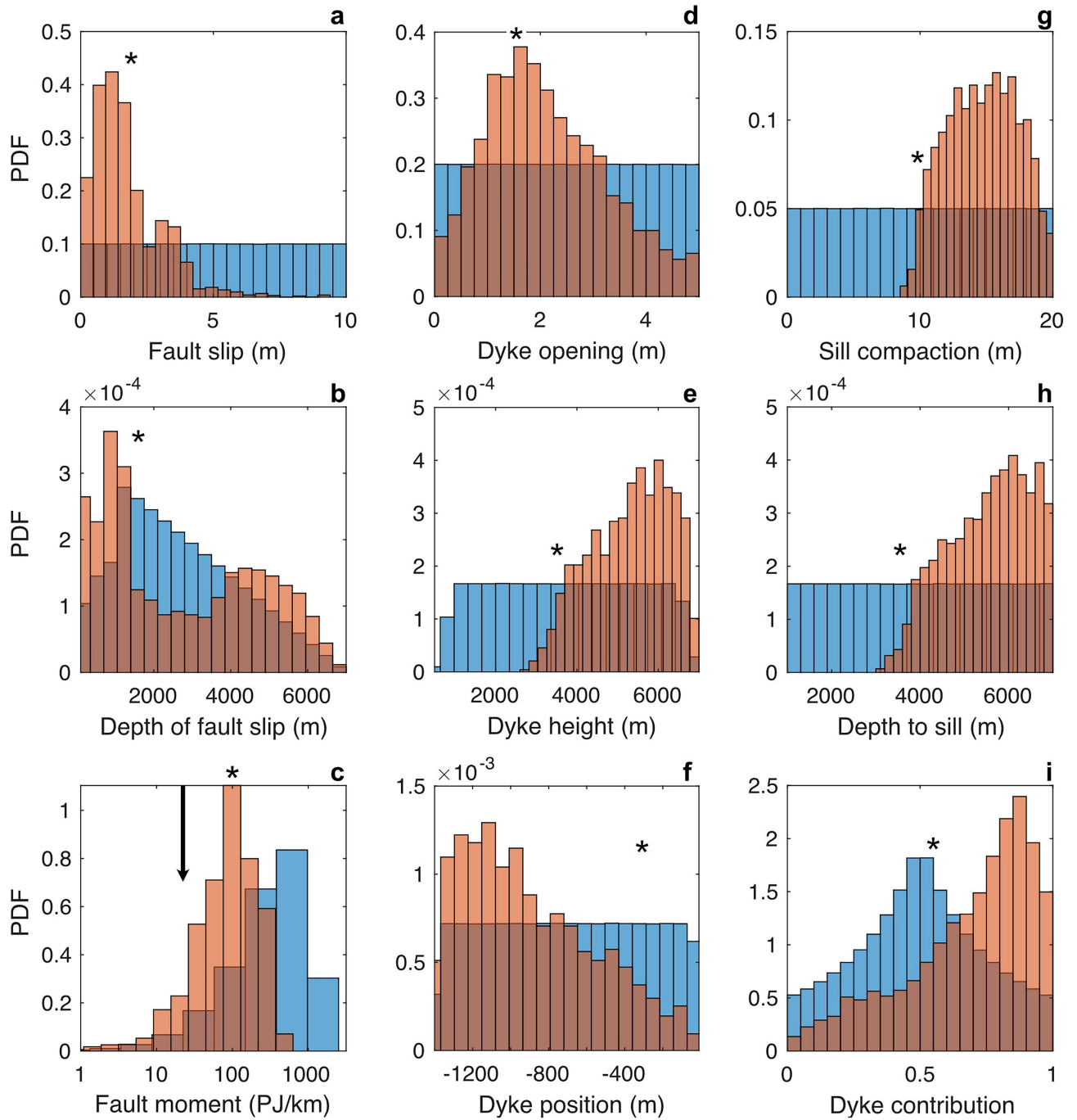


Extended Data Fig. 3 | Longer-term evolution of the direct acoustic-ranging baselines across the axial valley and the Amsterdam TF. a, Baselines (blue curves) from transponder TP7 to transponders TP3–TP4–TP5–TP6–TP8–TP9 in the axial valley (ridge array) are in either extension (orange) or contraction (blue). Vertical axes: actual baseline length (left) and relative changes (right). Bottom plots show the evolution of the sound speed at TP7, on which the ranging measurements are based, and which varies, owing to increases in the

sea-bottom water temperature caused by the lava extrusions (Extended Data Fig. 2d). **b,** Baselines from transponder TP13 to transponders TP12–TP14–TP15 on either side of the Amsterdam TF (TF array). There is no sign of clear strike-slip displacement along the TF; data are obscured by unexplained cyclical changes in the sound speed at TP13 (bottom plot). Uncertainties after the event are large owing to the important tilt of all tripods caused by the series of large-magnitude earthquakes.

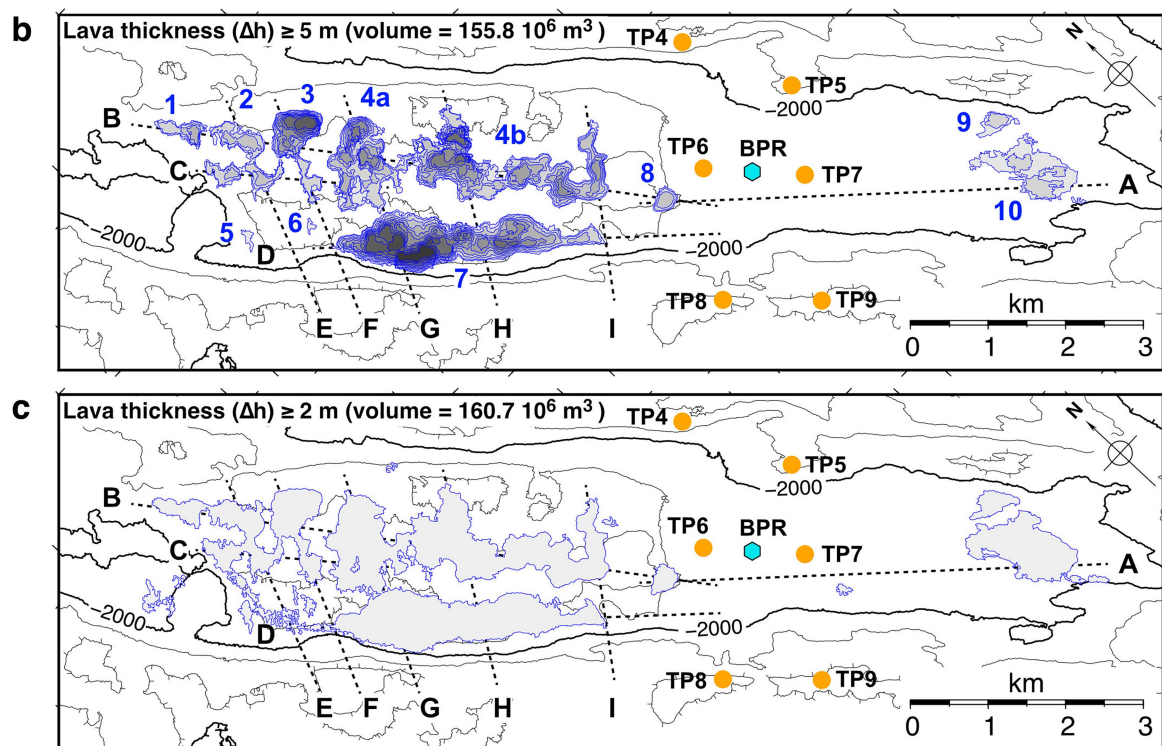
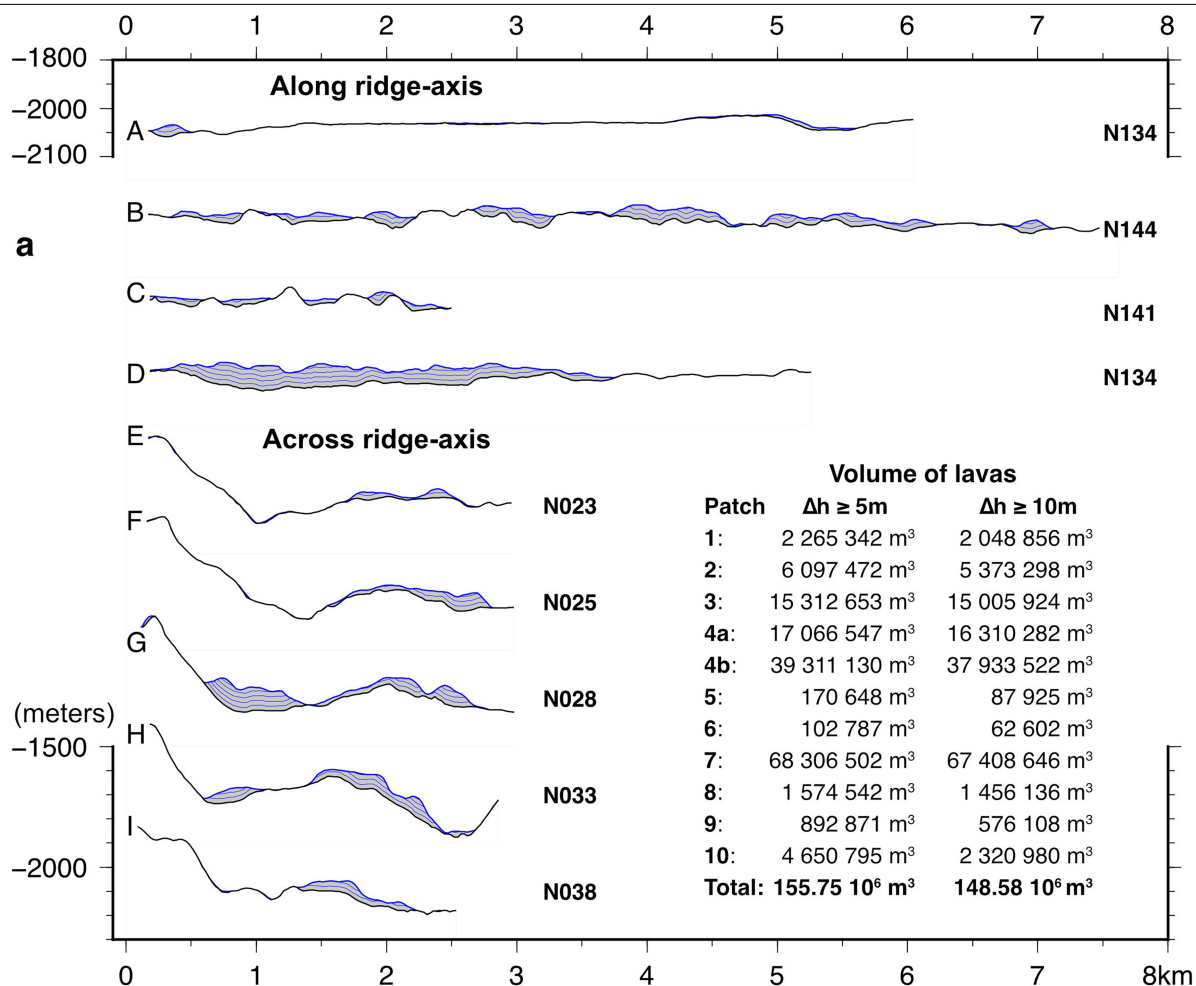


Extended Data Fig. 4 | Components of the horizontal and vertical displacements, and baseline changes in the model of Fig. 4, relative to TP7 ($x=0$). **a**, Horizontal displacements (positive towards northeast, negative towards southwest). Compaction of a magma lens below TP7 (that is, deflation of a reservoir owing to magma withdrawal) generates contraction on either side of TP7 (roughly within ± 2 km) and extension further outward. The dyke opening generates extension southwest of TP7, whereas the fault slip generates about 1 m of extension at the apex of the fault. **b**, Vertical displacements. The drainage of a magma lens (sill) accounts for most of the vertical subsidence measured at TP7 (triangle with error bar). It overwhelms the moderate uplift owing to the dyke emplacement. The fault slip generates 1.0 m of subsidence at its foot and a 0.5 m uplift of its shoulder. **c**, Contribution of each component to the observed baselines changes relative to TP7 (symbols with error bars). Combining all contributions—sill deflation, dyke opening and fault slip—yields the fit shown in Fig. 4 (with a total RMS misfit of 17 cm).



Extended Data Fig. 5 | Probability density function of the elastic model parameters for the 2,203 best-fitting solutions (out of 10 million random models). a–i, Asterisks (*) correspond to the model shown in Fig. 4. Blue histograms are the initial probability density functions (PDFs); brown histograms show the resulting range of best solutions (RMS misfit < 20 cm) for each of the inverted parameters. Horizontal axes give the full range of the seven variables tested in the models: fault slip (panels a and b), dyke (panels d–f), and

sill (panels g and h). Fault moment in panel c is derived from panels a and b. Dyke contribution to the total extension in panel i is derived from panels a, b and d, both for a fault dipping 60° . The arrow in panel c indicates the moment released by the series of $M_w \approx 5$ earthquakes in the axial valley (22.6 PJ km^{-1}), which is a small fraction of the total moment predicted by the models best fitting the measured displacements. The remainder reflects the moment taken up by aseismic slip during this quantum spreading event.

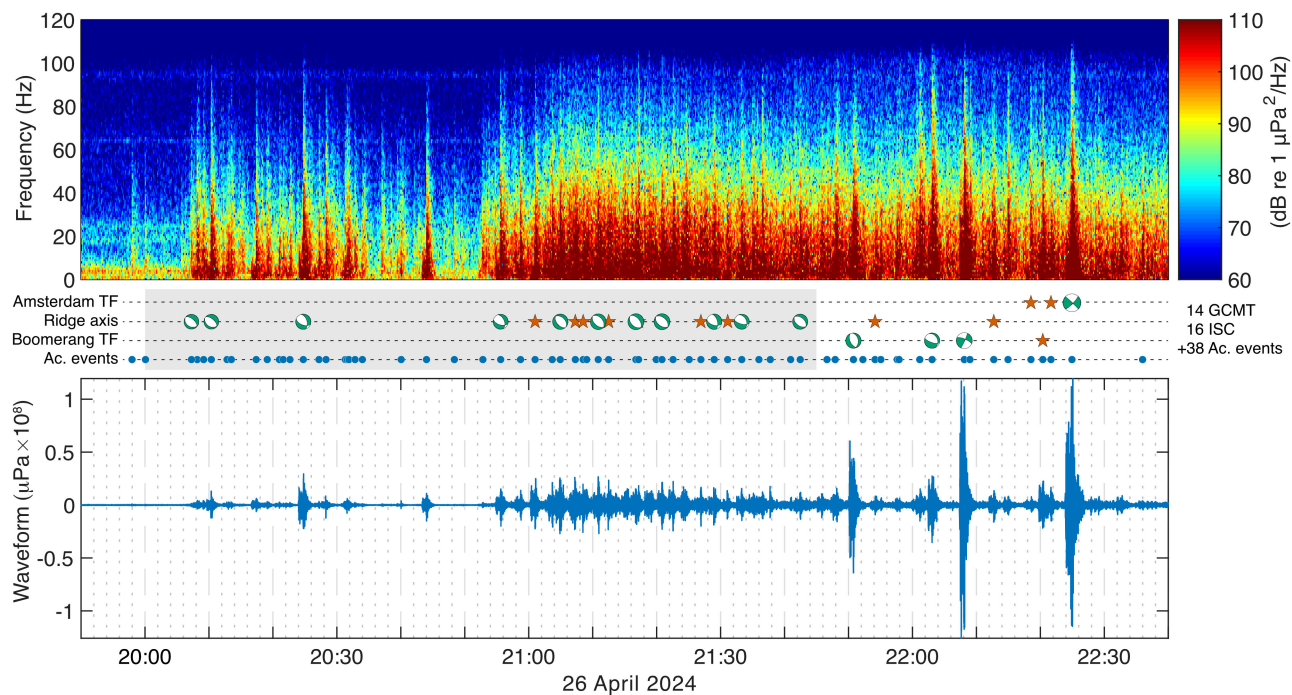


Extended Data Fig. 6 | See next page for caption.

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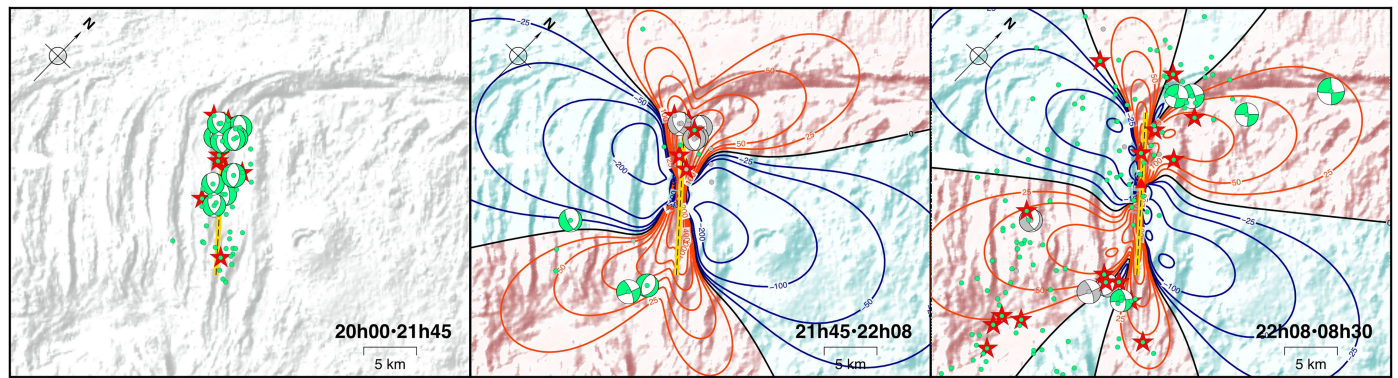
Extended Data Fig. 6 | Cross-sections and volumes of the new lava flows.
a, Across-axis sections (E to I) clearly show that lavas originated from two distinct sources, one centred on the former axial ridge, probably fed by the northwest-propagating dyke, and the other located at the foot of the valley wall, probably rooted to the dyke through the axial-valley bounding fault. Sections H and I show that, in places, lavas flowed down the slopes and filled

depressions. All cross-sections are at the same vertical scale, with isopach lines 20 m apart. **b**, Isopach map of the lava flows thicker than 5 m (same colour scale as in Fig. 3). **c**, Extension of the lava flows thicker than 2 m. Whether we consider elevation differences (Δh) greater than 2, 5 or 10 m to be notable, between the 2024 and 2025 bathymetric grids, the total volume of the new lava flows ranges between 149 and 160 million m³. Isobaths on the maps every 100 m.



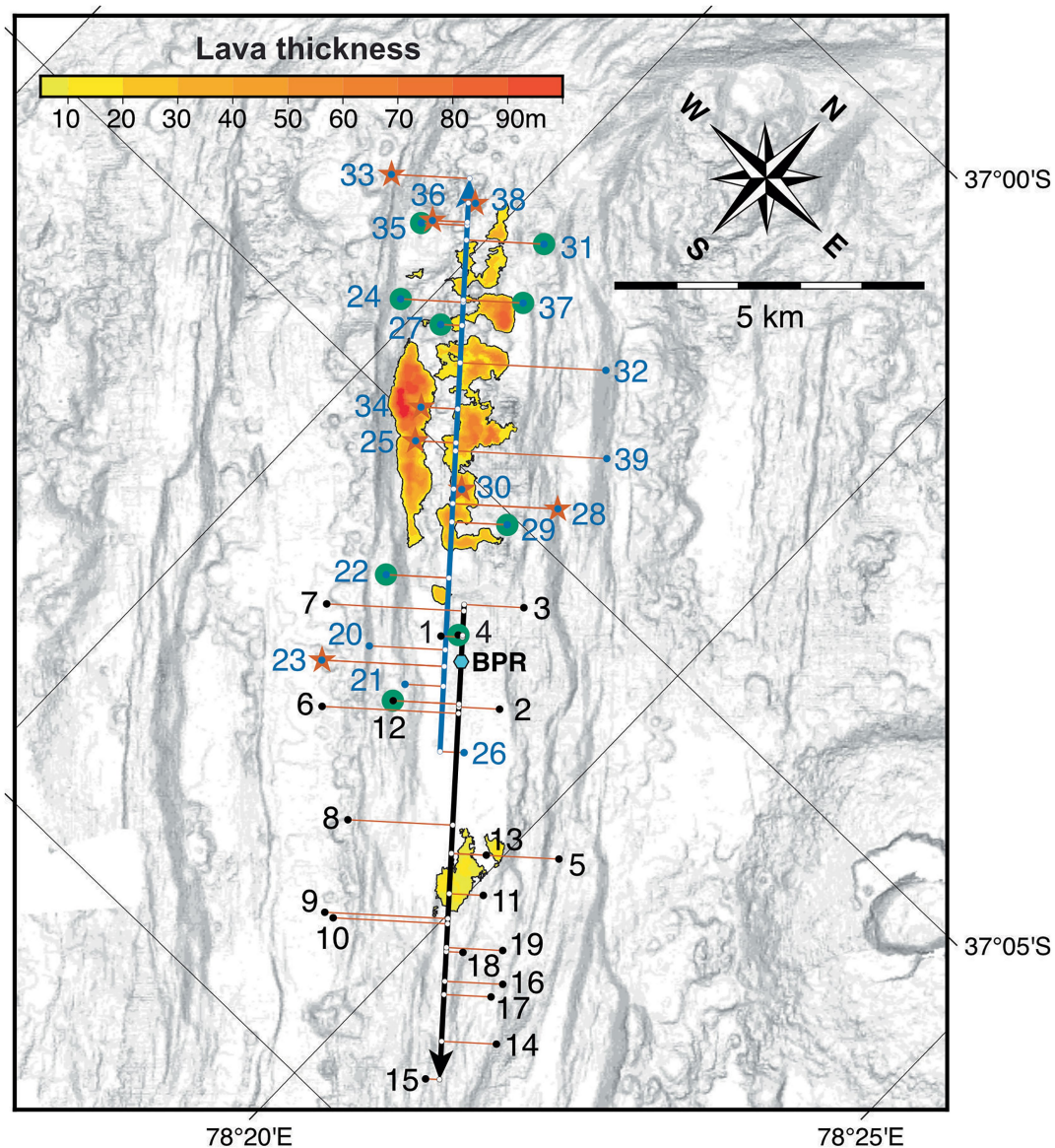
Extended Data Fig. 7 | Hydroacoustic spectrogram and waveform at the central hydrophone (central star in Fig. 1a) showing the onset of the 26 April 2024 seafloor spreading event and the sharp increase of T-wave and H-wave events after 20:50. The middle panel shows the arrival times of the

events shown in Fig. 1b and their distribution between the ridge axis and the two abutting transforms. The shaded area corresponds to the dyke propagation shown in Fig. 2a.



Extended Data Fig. 8 | Main phases of the 26 and 27 April 2024 seafloor spreading event and induced changes in Coulomb stresses. Left, initial dyke propagation (gold line) triggered by and/or inducing normal faulting along the walls bordering the axial valley. Background is the shaded bathymetry (oblique Mercator). Dyke propagation later triggered the reactivation of the southwestern diffuse Boomerang TF (centre), as predicted by the induced changes in Coulomb stresses, and ultimately reactivated the northeastern

Amsterdam TF (right). Positive and negative Coulomb stresses, shown in red and blue colours, respectively, with contours in kPa, are calculated for strike-slip receiver faults oriented N024 in the central panel (Boomerang TF) and N049 in the right panel (Amsterdam TF) and for a propagating dyke 1 m wide. Coloured seismic (GCMT, ISC, stars) and hydroacoustic (dots) events occurred in the time windows shown; greyed symbols are events preceding the starting time of each panel.



Extended Data Fig. 9 | Map view of the two early dyke propagations shown in Fig. 2a (oblique Mercator view). Numbers give the event relative chronology, in black for the southeastward propagating dyke and in blue for

the northwestward propagating dyke (stars, ISC; green circles, GCMT; dots, AUH catalogues). Coloured patches are the new lava fields (>5 m thickness); background image outlines the slopes of the seafloor.

Extended Data Table 1 | Chronology and locations of the large seismic events (as numbered in Fig. 1b)

Nbr	Longitude [°E]	Latitude [°S]	UTC Date & Time	Magnitude	Location	Catalogue
1	78.2981	-37.1019	2024-04-26 20:09:21.25	Mw=4.9	Axial valley	GCMT
2	78.2978	-37.1159	2024-04-26 20:23:45.72	Mw=5.1	Axial valley	GCMT
3	78.2803	-37.1029	2024-04-26 20:54:37.19	Mw=5.0	Axial valley	GCMT
4	78.2828	-37.1189	2024-04-26 21:00:01.93	mb=4.6	Axial valley	ISC
5	78.2461	-37.0714	2024-04-26 21:03:54.13	Mw=5.1	Axial valley	GCMT
6	78.2667	-37.0853	2024-04-26 21:06:15.19	mb=4.8	Axial valley	ISC
7	78.3432	-37.1449	2024-04-26 21:07:34.42	mb=4.5	Axial valley	ISC
8	78.2549	-37.0700	2024-04-26 21:09:50.33	Mw=5.2	Axial valley	GCMT
9	78.2951	-37.0778	2024-04-26 21:11:27.26	mb=4.6	Axial valley	ISC
10	78.2903	-37.0848	2024-04-26 21:15:43.41	Mw=5.3	Axial valley	GCMT
11	78.2794	-37.0857	2024-04-26 21:18:06.72	mb=4.8	Axial valley	ISC
12	78.2584	-37.0504	2024-04-26 21:19:46.57	Mw=5.3	Axial valley	GCMT
13	78.2285	-37.0588	2024-04-26 21:23:12.42	mb=4.6	Axial valley	ISC
14	78.2631	-37.0810	2024-04-26 21:25:53.82	mb=4.5	Axial valley	ISC
15	78.2389	-37.0610	2024-04-26 21:27:57.48	Mw=5.1	Axial valley	GCMT
16	78.2401	-37.0595	2024-04-26 21:30:02.51	mb=4.5	Axial valley	ISC
17	78.2633	-37.0590	2024-04-26 21:32:16.18	Mw=5.0	Axial valley	GCMT
18	78.2437	-37.0532	2024-04-26 21:34:07.06	mb=4.4	Axial valley	ISC
19	78.2625	-37.0616	2024-04-26 21:41:24.25	Mw=5.0	Axial valley	GCMT
20	78.2559	-37.0542	2024-04-26 21:44:46.97	mb=4.7	Axial valley	ISC
21	78.3375	-37.1834	2024-04-26 21:49:53.76	Mw=5.1	Boomerang TF	GCMT
22	78.2558	-37.0559	2024-04-26 21:53:07.00	mb=4.6	Boomerang TF	ISC
23	78.2262	-37.1891	2024-04-26 22:02:12.22	Mw=5.1	Boomerang TF	GCMT
24	78.3275	-37.1988	2024-04-26 22:07:14.91	Mw=5.3	Boomerang TF	GCMT
25	78.2935	-37.0630	2024-04-26 22:11:41.47	mb=4.5	Axial valley	ISC
26	78.1591	-37.0455	2024-04-26 22:17:28.31	mb=4.6	Amsterdam TF	ISC
27	78.3263	-37.1785	2024-04-26 22:19:29.45	mb=4.5	Boomerang TF	ISC
28	78.2275	-37.0092	2024-04-26 22:20:34.48	mb=4.5	Amsterdam TF	ISC
29	78.3661	-36.9231	2024-04-26 22:23:43.96	Mw=5.9	Amsterdam TF	GCMT
30	78.3439	-37.1743	2024-04-26 22:55:03.76	mb=4.6	Axial valley	ISC
31	78.2593	-37.0116	2024-04-26 23:23:18.37	Mw=5.4	Amsterdam TF	GCMT
32	78.2156	-37.1857	2024-04-26 23:44:47.76	mb=4.4	Boomerang TF	ISC
33	78.3684	-37.1788	2024-04-27 00:06:36.18	mb=3.9	Boomerang TF	ISC
34	78.3601	-37.1844	2024-04-27 00:42:40.07	Mw=5.0	Boomerang TF	GCMT
35	78.2948	-37.2581	2024-04-27 01:28:41.09	mb=4.0	Boomerang TF	ISC
36	78.2765	-37.2785	2024-04-27 01:31:58.32	mb=4.0	Boomerang TF	ISC
37	78.3336	-37.1824	2024-04-27 02:07:41.70	mb=3.8	Boomerang TF	ISC
38	78.2623	-37.0789	2024-04-27 02:31:04.03	mb=3.8	Axial valley	ISC
39	78.4092	-37.1977	2024-04-27 02:51:44.96	mb=3.9	Boomerang TF	ISC
40	78.2765	-37.2676	2024-04-27 02:55:39.02	mb=4.0	Boomerang TF	ISC
41	78.3170	-36.9896	2024-04-27 03:57:33.14	Mw=5.1	Amsterdam TF	GCMT
42	78.2469	-37.0211	2024-04-27 08:04:26.96	Mw=5.2	Amsterdam TF	GCMT
43	78.2778	-37.0236	2024-04-27 08:21:03.95	mb=4.7	Amsterdam TF	ISC
44	78.3126	-37.2504	2024-04-28 02:49:43.64	Mw=5.0	Boomerang TF	GCMT
45	78.2655	-37.0067	2024-04-29 03:39:45.09	mb=3.9	Amsterdam TF	ISC

All events were relocated from the hydroacoustic data. Magnitudes Mw and mb from the GCMT and ISC catalogues, respectively.