An immense shield volcano within the Shatsky Rise oceanic plateau, northwest Pacific Ocean

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Most oceanic plateaux are massive basaltic volcanoes. However, the structure of these volcanoes, and how they erupt and evolve, is unclear, because they are remote and submerged beneath the oceans. Here we use multichannel seismic profiles and rock samples taken from Integrated Ocean Drilling Program core sites to analyse the structure of the Tamu Massif, the oldest and largest edifice of the Shatsky Rise oceanic plateau in the north-western Pacific Ocean. We show that the Tamu Massif is a single, immense volcano, constructed from massive lava flows that emanated from the volcano centre to form a broad, shield-like shape. The volcano has anomalously low slopes, probably due to the high effusion rates of the erupting lavas. We suggest that the Tamu Massif could be the largest single volcano on Earth and that it is comparable in size to the largest volcano in the Solar System, Olympus Mons on Mars. Our data document a class of oceanic volcanoes that is distinguished by its size and morphology from the thousands of seamounts found throughout the oceans.

Many geoscientists consider that oceanic plateaux and continental flood basalt provinces (CFBP) have similar origins and are caused by massive eruptions associated with the arrival of the rising head of a hot mantle plume at the base of the lithosphere[1–4]. An alternative explanation is decompression melting of fertile upper mantle, without a significant thermal anomaly, beneath zones of lithospheric extension or fractures[5,6]. A third hypothesis is formation by meteorite impacts[7], but there is scant evidence to support this idea. However they come about, it is clear that such large igneous provinces result from a massive flux of material from the Earth's interior and give important clues about mantle dynamics. What is unclear is the structure and evolution of these large volcanic structures.

Shatsky Rise is a large plateau with a volume of $\sim 2.5 \times 10^6$ km^3 and total area similar to Japan or California[8]. Magnetic lineations show that it formed near a triple junction during Late Jurassic and Early Cretaceous time[9] (Fig. 1). Interaction of volcanism with the plate boundaries is inferred from magnetic anomalies and the observation that the triple junction followed the axis of the plateau as it was emplaced[8,9]. Three large edifices make up the bulk of Shatsky Rise, of which the largest and oldest is Tamu Massif, located at the southwest end of the plateau (Fig. 1). Basalts cored from Ocean Drilling Program (ODP) Site 1213 on Tamu Massif (Fig. 1) yielded a radiometric age of 144.6 ± 0.8 Myr (ref. 10). This date is approximately the same as the age of magnetic lineations in the surrounding sea-floor, indicating that the volcanic edifice formed near the triple junction spreading ridges. The smaller massifs, Ori and Shirshov (Fig. 1), and a low ridge were formed subsequently along the trace of the triple junction[8,9].

Core samples and seismic reflection profiles

Samples of Shatsky Rise igneous rock were recovered in cores at Site 1213 and Integrated ODP (IODP) Sites U1346–U1350

(refs 11,12; Fig. 1). Although pillow lavas indicative of eruptions at low rates of effusion[13,14] were recovered at several sites, the outstanding characteristic of Tamu Massif igneous sections is massive flows (analogous to 'massive sheet flows' of ref. 15) up to ~ 23 m thick cored at Sites 1213 and U1347 (Fig. 2). Such flows are hallmarks of the voluminous eruptions that build CFBP (refs 15–18). They travel long distances from their source vents owing to a high effusion rate, low viscosity and efficient thermal insulation[19,20]. Similar massive flows were cored from Ontong Java Plateau[21] (Fig. 2) and the coincidence implies that massive flows are characteristic of oceanic plateau eruptions. Moreover, the similar styles of volcanism strengthen the analogy of oceanic plateaux and CFBP. Cores from Ori and Shirshov massifs also recovered massive flows, but these are much thinner and make up progressively less of the cored section[11,12], implying that massive eruptions waned as Shatsky Rise evolved.

Although recovered cores are informative, our ability to use them to characterize Shatsky Rise is limited because they constitute a small sample of a huge volcanic feature (only ~ 50–175 m penetration of a volcanic edifice that rises 3–4 km from the ocean floor). For a better understanding of the structure of Shatsky Rise, MCS (multichannel seismic) reflection profiles were collected over Shatsky Rise (Fig. 1) by the R/V *Marcus G. Langseth* (cruises MGL1004, MGL1206). These data were collected with a 6-km, 480-channel hydrophone array (streamer) and a 36-airgun array (108.2 l volume) as the source. Because of the large source, seismic sections show deep penetration (Figs 3, 4) into the igneous crust: 1.0–2.5 s two-way travel time, or ~ 2–5 km assuming a seismic wave velocity of 4.0 km s^{-1} for the upper igneous crust[22].

Intra-basement reflectors

Line A–B (Figs 1, 3) is unique because it crosses an entire oceanic plateau and shows a remarkable symmetry around the easternmost

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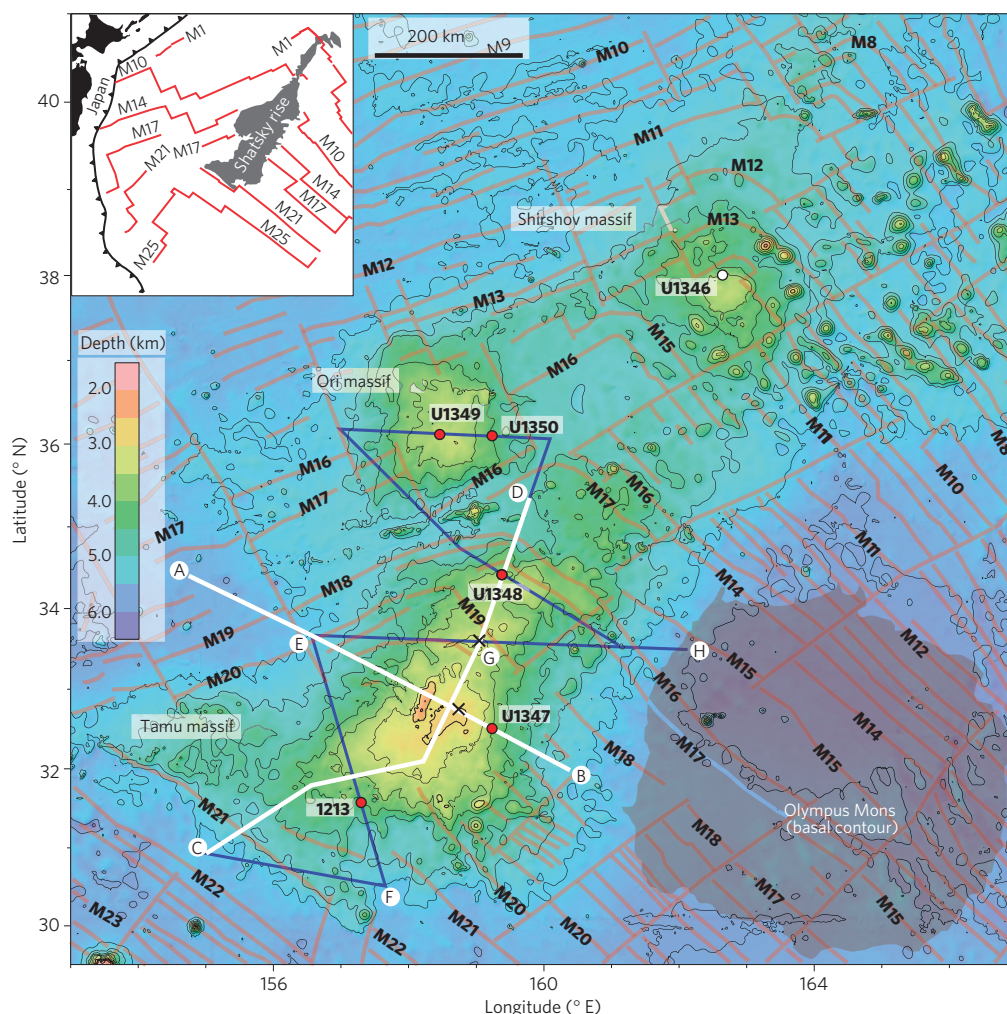
Figure 1 | Shatsky Rise bathymetry[45] and tectonic map. Red lines show magnetic lineations and fracture zones[9]. Blue and white lines show MCS reflection profiles discussed in the text; heavy white lines denote the sections shown in Figs 3 and 4. Red dots show the locations of ODP and IODP drill sites. Crosses denote the locations of summit calderas. Inset depicts the location of Shatsky Rise relative to Japan, subduction zones (toothed lines), and the magnetic anomaly pattern. Grey area (lower right) shows the footprint of Olympus Mons (Mars) at the same scale. Letters next to seismic lines indicate the section end points shown in Figs 3 and 4.

of two peaks (at shotpoint 4400). Intra-basement reflectors diverge from this summit and decline down the flanks to the adjacent abyssal sea-floor. Line C–D (Figs 1 and 4) gives a similar picture paralleling the elongation axis of Tamu Massif. It likewise shows intra-basement reflectors dipping away from the summit (as do other seismic lines, see Supplementary Figs S6–S8). Typical flank slopes of this edifice are 1°–1.5° at the most and <0.2°–0.5° near the base, values that are significantly shallower than the >5° typical of common seamounts[23]. Although Tamu Massif slope angles cannot be measured precisely because seismic lines are sparse and may not be oriented parallel to the maximum dip, it is likely that reflector dips are nearly perpendicular to bathymetry contours, so Line A–B should show the greatest slope (Fig. 3). Because of the small dip angle, slopes measured on other lines are not significantly different.

Intra-basement reflectors are piecewise-continuous and form subparallel-stratified sequences (Fig. 5). Individual reflectors are typically traced for ~5–20 km, but adjacent reflectors can often be connected to imply longer, piecewise-continuous horizons. Furthermore, the overall pattern of stacked reflectors can be followed for several hundred kilometres down the shallow flank slopes to adjacent basins (Figs 3–5 and Supplementary Figs S3–S9).

Figure 5 shows detail of the dipping intra-basement reflectors on the MCS Line A–B (see also Supplementary Figs S4–S5).

Intra-basement reflectors are strongest and most continuous near the top of the igneous pile ('igneous basement' surface). Deeper reflectors become progressively weaker and less continuous with depth as the seismic signal becomes scattered and attenuated. In contrast to the smooth, continuous horizons in the sedimentary cap, inspection of intra-basement reflectors reveals significant roughness as well as discontinuities and changes of slope (Fig. 5). Undulations of up to a few tens of milliseconds are observed, indicating rough volcanic topography. In some spots, reflector slopes can be larger than average, with some groups having local dips of up to ~3°–5°. Some lateral variability is likely an artefact of shifting interference patterns caused by changes in unit thickness and roughness as well as seismic artefacts, such as ringing, between-layer multiples, and scattering[24,25]. Nevertheless, reflector individuality and the resemblance to expected layering (that is, lava flows) implies that most of the reflectors have geological significance.

Core and borehole logging data from Site U1347 allow us to construct a synthetic seismic model (Supplementary Fig. S2) to guide interpretation of the MCS profiles. Intra-basement reflectors apparently result from thick, dense, massive flows, thick packages (groups) of lava flows with similar properties, as well as the contrast of lava flows with occasional thick layers of inter-flow
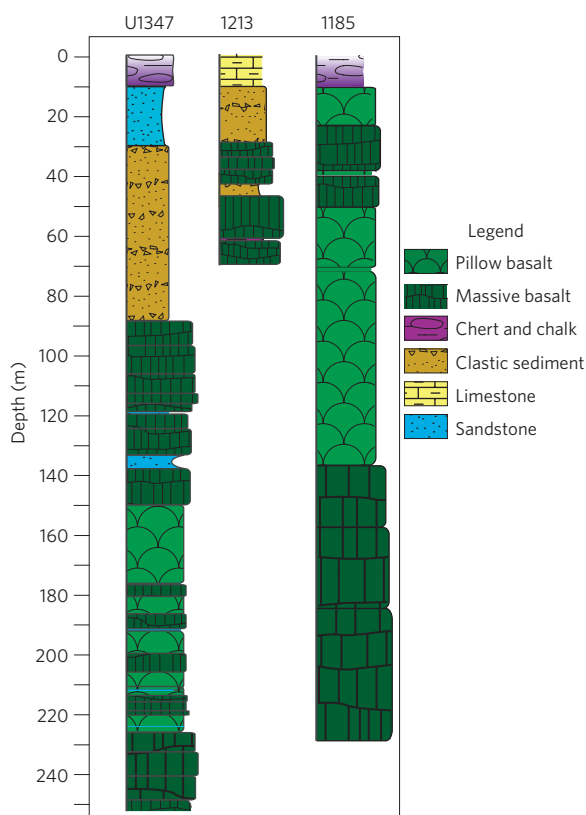
Figure 2 | Lithology of Tamu Massif igneous sections and comparison with ODP Site 1185 on Ontong Java Plateau. Columns have been shifted in depth to align the tops of igneous sections. Site 1213 is from ODP Leg 198 (ref. 46), Site 1185 from ODP Leg 192 (ref. 21), and Site U1347 is from IODP Expedition 324 (ref. 11).

sediments. Lava flow packages are imaged because most flows are too thin to be imaged individually by the low-frequency MCS data owing to the long wavelength of the acoustic waves (∼50–100 m in basement; Supplementary Information). MCS profiles from other oceanic plateaux show similar intra-basement reflectors, which are interpreted as lava flow surfaces[26–28]. Modelling and correlation of drill core and seismic data from Ontong Java Plateau also indicate that intra-basement reflectors are caused by acoustic impedance contrasts between packages of alternating massive flows and pillow lavas[28]. Given this evidence, we interpret the intra-basement reflectors as surfaces of lava flow units.

Tamu Massif structure

On MCS lines crossing the summit of Tamu Massif (Figs 3, 5 and Supplementary Figs S5, S7 and S8), intra-basement reflectors extend downhill from the summit apex, implying that this feature is the flow source. On several profiles, a depression is noted at the summit apex, ranging from ∼55–170 m in depth and ∼3–5 km across. It is seen on Line A–B (Figs 1, 5) as well as Line 14C from cruise TN037, located ∼10 km farther south[29], implying that the depression is elongated N–S. Farther north, a similar geometry is observed. The depression is ∼15 km long on the N–S oriented Line C–D (Fig. 4) and ∼5 km wide on the E–W oriented Line E–G–H (Supplementary Figs S5 and S8), again implying N–S elongation. Both the dimensions and locations are similar to those of calderas on large, active shield volcanoes[30–32], suggesting a similar origin. Unfortunately, no seismic lines cross the summit in the ∼100 km between the two spots where these depressions are observed, so it is uncertain whether similar depressions occur in between or whether they are connected.

Calderas and pit craters are common collapse features observed on basaltic shield volcanoes, usually at the summit or along the apex of a rift zone where shallow magma chambers are drained by eruptions[30–32]. These features are often near eruptive source vents and probably the same is true for Tamu Massif. Beneath each depression, the acmes of intra-basement reflectors are observed to have similar shapes and locations, demonstrating that the summit did not migrate significantly during the later history of the volcano. The narrow summit and calderas do not seem to extend far from the Tamu Massif summit. A seismic profile (E–F; Fig. 1 and Supplementary Fig. S6) crossing the Tamu Massif axis lower on the south flank exhibits a rounded profile without a depression. Two cruise TN037 profiles[29] (Lines 14B, 14D) located on the south side of the summit, between profiles A–B and E–F, look the same. This contrasts with Hawaiian and other large shield volcanoes, which often have narrow, elongated rift zones that extend down the volcano flanks and are the source for many shield-building eruptions[30,31]. The geometry of Tamu Massif suggests that it formed mainly from summit eruptions.

In contrast to Line A–B, which shows a slightly convex-upward shape to the Tamu Massif flanks, Line C–D shows a more rounded, shield-like shape. This difference is consistent with the latter seismic profile following the eruptive axis of the volcano. Hawaiian shield volcanoes also show this difference, with the iconic shield shape being observed on profiles oriented along rift zone axes in contrast with steeper cross-axis profiles. Lava flows on Line A–B dip away from the volcano centre only, whereas undulations of horizons are observed in the upper part of the volcano on Line C–D, especially near the middle of the profile and at depth. These undulations probably represent overlapping of flows from adjacent along-axis eruption sequences. In some places, they may indicate longer-term volcanic centres. Convex-upward intra-basement reflectors at 1–2 s beneath the basement surface on Line C–D at around shotpoints 4000 (segment A) and 2500 (segment B) may indicate buried eruptive centres (arrows, Fig. 4). Two-way travel times imply depths of ∼3 km below the basement surface and thus represent morphology early in the volcano history. Alternatively, these undulations may simply indicate three-dimensional geometry as the seismic line strays from the buried eruption axis. Nevertheless, the seismic data show that in the upper ∼1.5 s, lava flows evened out the topography to construct the current shield shape.

Although Tamu Massif has a broad, dome shape, there are significant secondary volcanic features. A ∼1-km tall, secondary peak (Toronto Ridge) on Line A–B (shotpoints 5750–6000, Fig. 3) disrupts the symmetry of Tamu Massif, but on the basis of several observations it is not a significant volcanic locus. Although it partly masks the seismic section below, deeper reflectors trend downslope without significant apparent distortion or interruption, indicating the peak was not a long-term flow source or barrier. Furthermore, shallow water fossils were recovered from deeper levels around the Tamu Massif upper flanks, so this peak would have been emergent and eroded were it coeval with the shield[8,11]. Last, its steeper slopes (∼5°) resemble those of small cones on the Tamu Massif flanks (Fig. 3), which are probably late-stage volcanic features, similar to parasitic cones observed on shield volcanoes[30]. Line C–D exhibits a broad hump on the north flank of Tamu Massif (shotpoints 4000–5400 on segment D). This feature was cored at IODP Site U1348, where mainly volcaniclastic material was recovered[11], indicating that it is also a secondary feature and not part of the primary basaltic shield. Thus, Tamu Massif is an enormous basaltic shield, mostly built from lava flows emanating from the centre of the volcano.
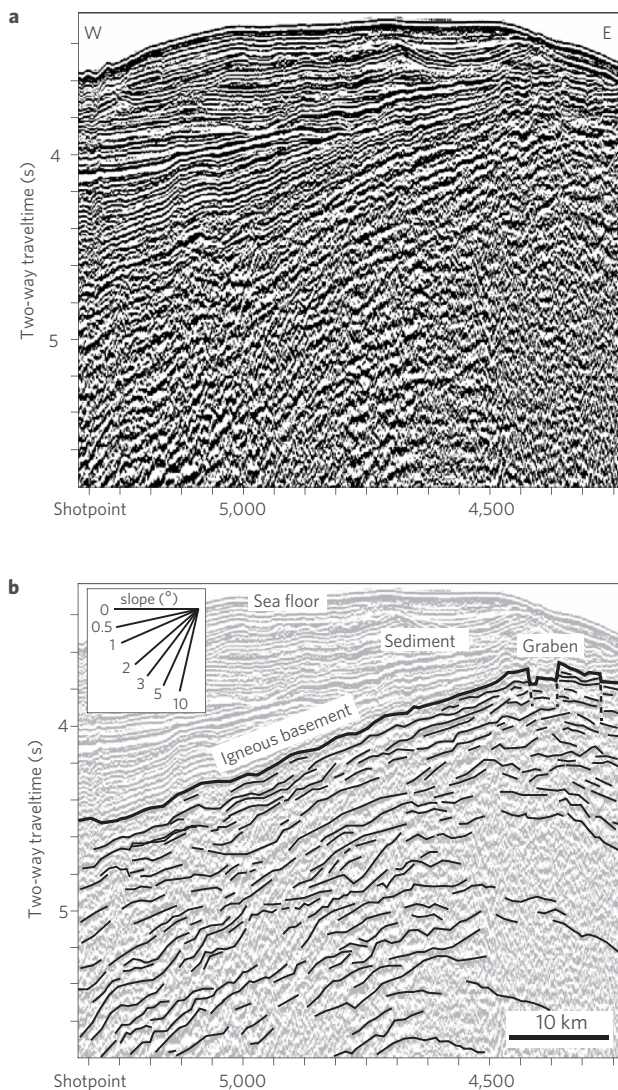
Implications for oceanic plateau volcanism

It is remarkable that Tamu Massif reveals itself to be one enormous shield volcano. Oceanic plateaux have long been recognized as massive volcanic features, but the geometry of magma-supplying
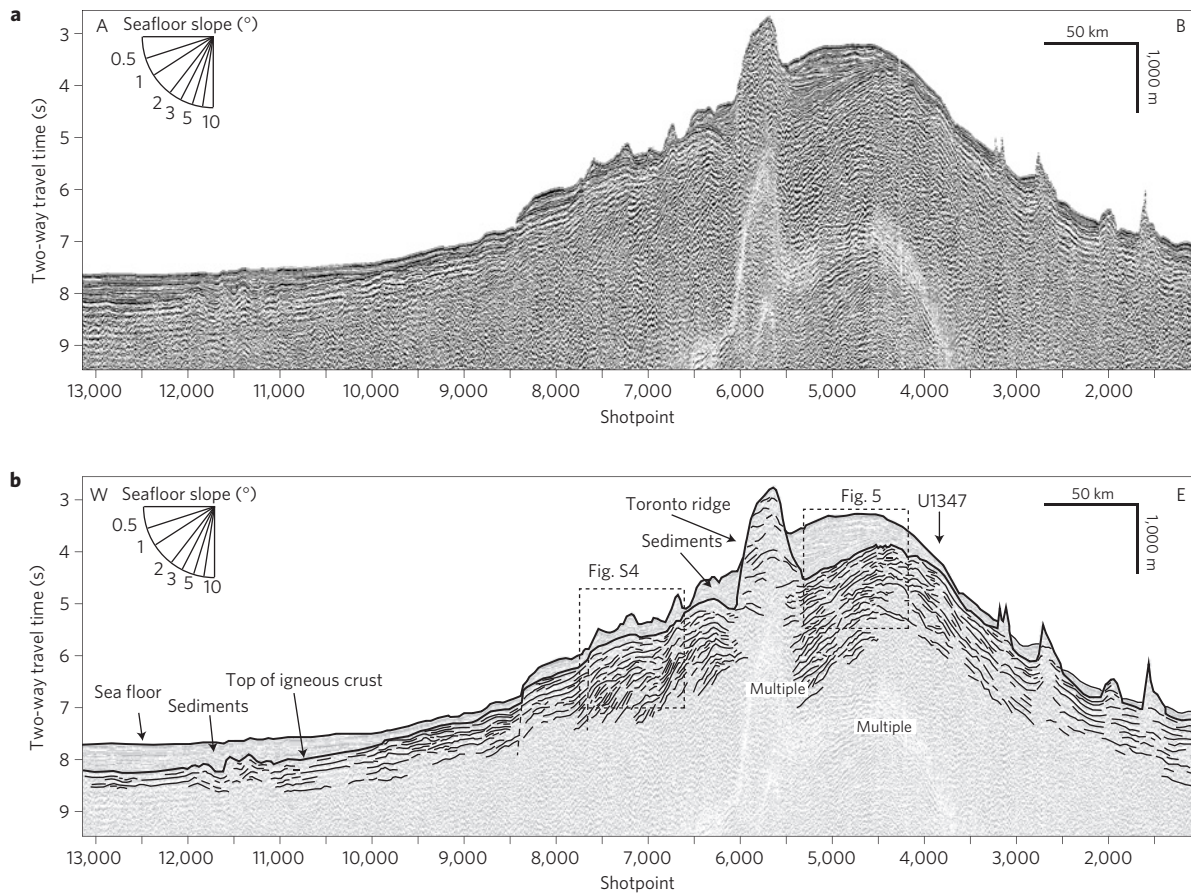
Figure 3 | MCS reflection Line A–B, across the axis of Tamu Massif. a, MCS data. **b**, Interpretation. Dark lines highlight the intra-basement reflectors. The location is shown in Fig. 1. MCS data have a nominal fold of 59 and have been processed with band-pass filtering, deconvolution, normal-moveout correction, stacking, and time migration. The arrow labelled U1347 shows the position of that IODP site. Dashed boxes show the locations of Fig. 5 and Supplementary Fig. S4. Vertical exaggeration: 37:1.
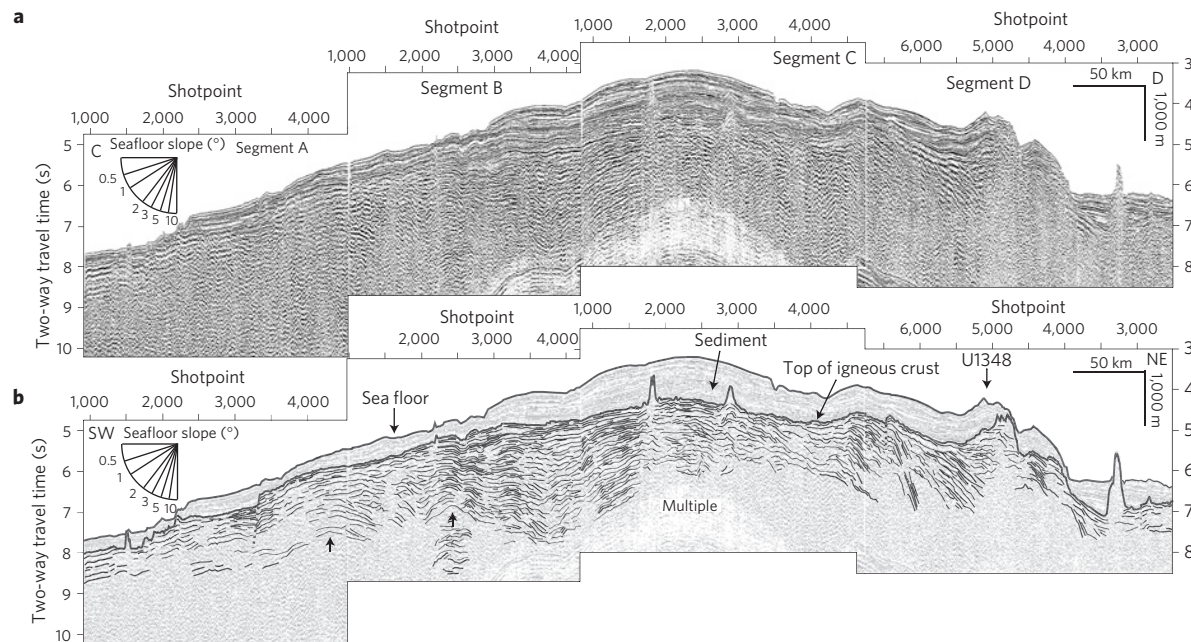
Figure 4 | MCS reflection Line C–D, along the axis of Tamu Massif. a, Montage of four seismic lines (segments A–D). **b**, Interpretation of seismic data montage. Conventions as in Fig. 3. Arrow labelled U1348 shows the position of that IODP Site. Heavy arrows in the subsurface show convex-upward reflectors that may indicate buried eruptive centres.

Figure 5 | Enlargement of a portion of the MCS reflection Line A–B to show intra-basement reflector detail. a, MCS data. **b**, Interpretation of seismic data. Vertical exaggeration: 25:1. Other conventions as in Fig. 3. Location shown in Fig. 3.

across at the base, with typical flank slopes[23] ≥5°. Figure 1 shows normal seamounts in the vicinity of Shatsky Rise, and they are dwarfed in size by Tamu Massif. Samples from seamounts are often pillow lavas, which form at low effusion rates, typically on steep slopes[13,14]. Shatsky Rise was built by effusive eruptions that formed thick sheet flows[15,39] and travelled large distances to give Tamu Massif its distinctive low slopes, large diameter, and rounded morphology. Other oceanic plateaux have similar morphologies and probably formed in the same way.

Tamu Massif is the largest known single, central volcano in the world. There are certainly larger volcanic complexes, such as several CFBP and the Ontong Java and Kerguelen oceanic plateaux[2]. The structures of these larger features are poorly known and they may have formed as composite features from multiple sources[17,26,28]. If Tamu Massif is unique in being a single volcano, why is it so? The answer may be the rate of movement of the melting anomaly relative to the overriding tectonic plates on which the volcanic products were emplaced. During the construction of Shatsky Rise, the melting anomaly traversed ~900 km during ~12 Myr (ref. 9), (~7.5 cm yr^{-1}). This rapid motion combined with temporal pulses of volcanism allowed individual volcanic piles to form without significant merging or overlapping. Tamu Massif may therefore represent the basic building block of a large oceanic plateau, the product of a single massive pulse of igneous emplacement.

The observation that Tamu Massif is a single volcano provides an important framework for synthesizing relevant geophysical and geochemical data: observed variability occurs within the framework of a single edifice. Geochemical data from Tamu Massif samples indicate that the lavas are almost entirely of a single type, with low geochemical variability[40], as might be expected from a single volcano from a single source. Irrespective of melt anomaly migration rate, the observation that Tamu Massif formed as a single volcano may be an important constraint on the physics of melt migration through the lithosphere. A large amount of melt was focused at a single location. Still to be explained is how this large volume of magma formed and was stored in the mantle and crust before eruption. Probable calderas at the summit of Tamu Massif imply shallow, crustal storage of a least a portion of the erupted magma. This agrees with geochemical data indicating that Tamu Massif basalts fractionated at depths of ~6 km of less[40]. However, the small size of these calderas raises a question of where the large quantities of magma required for large sheet flows resided before eruption. The ~6 km fractionation depth corresponds to the boundary between upper and lower crust in refraction data[22]. This coincidence suggests that the lower crustal layer of Tamu Massif plays the role of a magma reservoir, similar to the lower layer of the oceanic crust in normal spreading regimes[41].

Similar seismic reflection characteristics noted on several oceanic plateaux[26–28] imply that effusive volcanism is common to oceanic plateaux and occurs throughout the ocean basins. Tamu Massif seismic lava flow images also exhibit similarities to dipping layers on volcanic continental margins, termed seaward-dipping reflector (SDR) sequences[25,42,43]. Aside from having inclined reflectors that represent massive lava flows, the settings are different. SDR accumulate on transitional crust during the breakup of volcanic continental margins, whereas Tamu Massif formed far from continents. SDR usually diverge toward the source and are sometimes arcuate in cross-section, a result of differential subsidence of the continental margin. The subsidence results either from accumulation of flows near the vent[42] or by the formation of half-grabens during extension[44]. Tamu Massif reflectors record lava flows descending the volcano flank. Their parallelism implies that little differential subsidence occurred. This observation implies that Tamu Massif lava flows spread across its surface so that no location was depressed owing to excessive accumulation. Another difference with SDR is that there is no evident connection to sea level for the Tamu Massif intra-basement reflectors, whereas some SDR form

vent systems and lava flows has been unclear. The same can be said for CFBP, which are thought to be constructed by fissure eruptions, perhaps from multiple locations[16–18,33]. The suspicion has been that oceanic plateaux are similar constructs, perhaps building up from multiple centres to generate their massive size. This is true, for example, for the volcanic edifice of the island of Hawaii, which consists of five individual shield volcanoes[31] despite the entire complex being significantly smaller than Tamu Massif. Likewise, the large edifice of Iceland is also a composite of large volcanoes[34]. Tamu Massif geometry gives a different picture: it is one large basaltic shield. It is a broad, rounded dome ~450 × 650 km with an area of 3.1×10^5 km^2, approximately the same as the British Isles or Olympus Mons on Mars (Fig. 1), which is considered the largest volcano in the solar system[35,36]. Although Olympus Mons seems to be a giant because it is >20 km in height, its volume is only ~25% larger[8,36]. It is taller because it is supported by thick lithosphere, whereas Tamu Massif was formed on thin lithosphere, so most of its ~30 km thickness is hidden as an isostatic crustal root[22].

Tamu Massif also seems to be a different class of volcano compared with common seamounts. There are 10^4–10^5 of the latter scattered across the ocean basins[37,38], typically tens of kilometres

subaerially and incorporate significant volcaniclastic sediment[25]. Although volcaniclastics occur on Tamu Massif, drilling results imply that inter-flow layers of such sediments make up a small portion of the basalt pile[11] (Fig. 2).

Geophysical data from Tamu Massif demonstrate that the huge volcanoes found on other solar system bodies have cousins here on Earth. The Earth variety is poorly understood because these monsters found a better place to hide—beneath the sea. Data from Shatsky Rise and other oceanic plateaux indicate that large volumes of material rose from the mantle to the lithosphere, perhaps in short periods of time, building great volcanic edifices. Whatever explanation is given for oceanic plateau formation, data from Tamu Massif require that it provide for the construction of an extraordinary shield volcano.

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Author contributions

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Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to W.W.S.

Competing financial interests

The authors declare no competing financial interests.