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A record of spontaneous subduction initiation in the Izu–Bonin–Mariana arc

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The initiation of tectonic plate subduction into the mantle is poorly understood. If subduction is induced by the push of a distant mid-ocean ridge or subducted slab pull, we expect compression and uplift of the overriding plate. In contrast, spontaneous subduction initiation, driven by subsidence of dense lithosphere along faults adjacent to buoyant lithosphere, would result in extension and magmatism. The rock record of subduction initiation is typically obscured by younger deposits, so evaluating these possibilities has proved elusive. Here we analyse the geochemical characteristics of igneous basement rocks and overlying sediments, sampled from the Amami Sankaku Basin in the northwest Philippine Sea. The uppermost basement rocks are areally widespread and supplied via dykes. They are similar in composition and age—as constrained by the biostratigraphy of the overlying sediments—to the 52–48-million-year-old basalts in the adjacent Izu–Bonin–Mariana fore-arc. The geochemical characteristics of the basement lavas indicate that a component of subducted lithosphere was involved in their genesis, and the lavas were derived from mantle source rocks that were more melt-depleted than those tapped at mid-ocean ridges. We propose that the basement lavas formed during the inception of Izu–Bonin–Mariana subduction in a mode consistent with the spontaneous initiation of subduction.

Recycling of lithospheric plates into the mantle is a major driver of the physical and chemical evolution of Earth. Subduction zones mark sites of lithosphere insertion into Earth's mantle, but we do not have a good understanding of how these zones are initiated or the accompanying compositional types and style of magmatism. Of all magma types emplaced at or near the surface of the Earth, those associated with subduction zones most closely match the average continental crust[1]; accordingly there has been sustained interest in the genesis and evolution of island arc magmas, and their significance with respect to continental crustal growth. On the basis of assumed ages of the current major subduction systems bordering the Pacific and along the Alpine–Himalayan Zone, McKenzie[2] suggested 'ridges start easily, but trenches do not'. Ignorance of subduction inception contrasts with our advanced understanding of oceanic crust creation from initial lithospheric rifting to development of a mid-ocean ridge. Gurnis *et al.*[3] noted half of all active subduction zones initiated in the Cenozoic in a variety of tectonic settings, including old fracture zones, transform faults, extinct spreading centres, and through polarity reversals behind active subduction zones, and concluded forces resisting subduction can be overcome in diverse settings accompanying the normal evolution of plate dynamics.

Among a number of proposed hypotheses, two general mechanisms, induced or spontaneous[3,4], seem relevant to initiation of one of the largest intra-oceanic subduction zones in the western Pacific, namely the Izu–Bonin–Mariana (IBM) system. Induced subduction initiation leading to self-sustaining descent of lithosphere into the mantle results from convergence forced by external factors such as ridge push or slab pull along-strike of a given system (for example, ref. 3). The Puysegur Ridge south of New Zealand may be an example. The IBM system has been suggested to represent an example of spontaneous initiation wherein subsidence of relatively old Pacific lithosphere commenced along a system of transform faults/fracture zones adjacent to relatively young, buoyant lithosphere[4]. The importance of transpressional forces in subduction initiation has also been emphasized[5]. Stern and Bloomer[6] proposed the earliest stages of volcanism accompanying spontaneous subduction zone nucleation are rift-associated and extensive perpendicular to the strike of the zone, rather than comprising the archetypal chain of stratovolcanoes that dominate mature arcs. The initial record of subduction initiation on the overriding plate resulting from these competing hypotheses should be distinct: induced subduction probably results in strong compression and uplift shedding debris into nearby basins, whereas spontaneous subduction commences with basement deepening before rifting, and seafloor spreading, potentially analogous to a number of ophiolites (for example, refs 3,6).

For the IBM system, the age and composition of initial magmatism (~52 Myr) preserved in the fore-arc basement and underlying peridotite have been determined[7], as has the subsequent magmatic evolution of the arc through the study of dredged and drilled materials, including ashes and pyroclastics recovered by ocean drilling[8,9]. The arc has experienced episodes of back-arc spreading in the Mariana Trough (7 Myr ago to present) and Shikoku and Parece Vela basins (~30–20 Myr ago), resulting in abandonment of the Kyushu–Palau Ridge (KPR) as a remnant arc[10]. Understanding the relationship of the northern portion of the KPR

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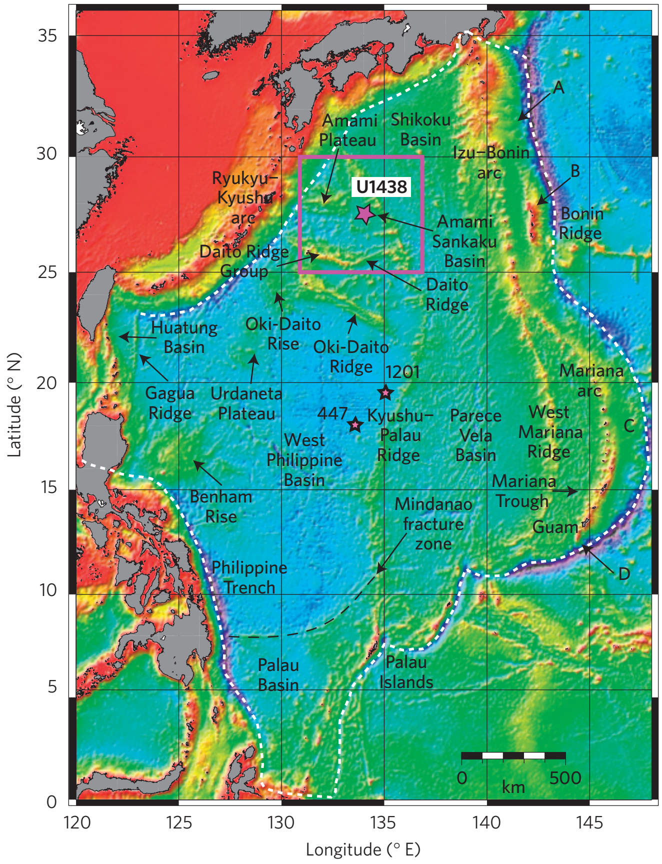

Figure 1 | Location of the Amami Sankaku Basin and the Kyushu–Palau Ridge. General setting and bathymetry (blue deep, red shallow) of the bounding trenches, basins and ridges comprising the Philippine Sea Plate, boundary outlined with a dashed white line. Locations of IODP Site U1438, ODP Site 1201, and DSDP Site 447 are shown by pink stars. Locations of Shinkai submersible dives in the IBM fore-arc are noted as A (ref. 22), B (ref. 23) and D (ref. 24). Location of DSDP Site 458 is noted as C (ref. 25). Pink-bounded box is shown in detail in Fig. 2.

to the basement underlying its western flank in the Amami Sankaku Basin (ASB; Fig. 1) seemed to offer the promise of a record of IBM inception complementary to that recovered by dredging and submersible operations in the fore-arc[7]. Taylor and Goodliffe[10], for example, had emphasized the strike of the KPR in this region (and the inferred Eocene trench) is at a high angle to all major extant features, such as the western and southern borders of the ASB and Amami Plateau–Daito Ridge, and concluded the IBM subduction zone did not initiate along any part of the pre-existing tectonic fabric, such as a transform fault.

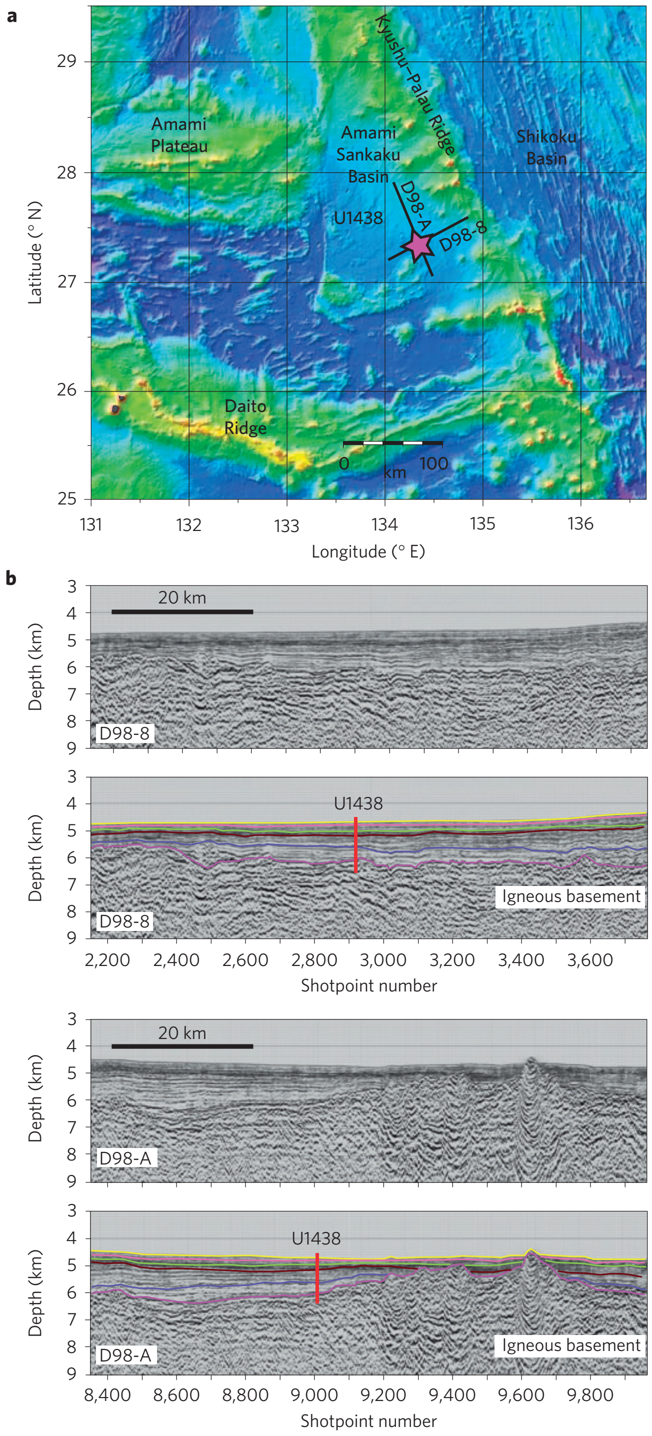

Figure 2 | Detailed bathymetry of the Amami Sankaku Basin, IODP Site U1438, and seismic survey lines. a, Bathymetry of the Amami Sankaku Basin, neighbouring Kyushu–Palau Ridge, and nearby Cretaceous-aged arcs of the Amami Plateau and Daito Ridge. Site U1438 is located at the intersection of the two multichannel seismic survey lines D98-A and D98-8. **b**, Seismic reflection images at Site U1428. The top two panels show the multichannel seismic line D98-8 (upper) and interpreted major reflectors (lower). The bottom two subpanels show multichannel seismic line D98-A (upper) and interpreted major reflectors (lower). Shotpoints fired every 50 m.

Amami Sankaku Basin—a key record of arc inception

The ASB is in the northwest of the Philippine Sea plate (PSP). The PSP is bounded by subduction zones and transform faults (Fig. 1), and has a complex tectonic and magmatic history. Plate tectonic reconstructions[11–13] place subduction inception ~50 Myr ago in the proto-Izu–Bonin arc (that is, previously assumed to be the KPR), concurrent Pacific plate motion change, cannibalizing former northwest–southeast-trending transform faults associated with the Izanagi–Pacific Ridge (for example, ref. 14). Subduction of the Izanagi–Pacific Ridge along eastern Asia ~60 Myr ago possibly initiated plate reorganization culminating in Pacific plate motion change 50 Myr ago relative to the Eurasian plate[12]. Since IBM inception, the PSP has migrated northwards, accompanied by clockwise rotation, mostly between 50 and 25 Myr ago (ref. 15). At subduction inception, a Cretaceous-age island arc system existed on the PSP, now preserved as the Amami Plateau–Daito–Oki-Daito ridges[13] (Fig. 1); arc conjugates are possibly preserved in the southern PSP in Halmahera and southern Moluccas[16]. Back-arc spreading behind this southern arc caused initial opening of the West Philippine Basin (WPB), isolating the Amami Plateau–Daito–Oki-Daito ridges. Plume-derived ocean island basalt (OIB)-like magmatism followed IBM initiation, endured from 51 to 45 Myr ago, and is preserved as the Benham Rise–Urdaneta Plateau–Oki-Daito Rise[17–19].

The ASB floor has a simple structure comprising up to 1.5 km of sediment overlying igneous oceanic crust (Fig. 2). Assuming a $V_p \sim 6\,\mathrm{km\,s^{-1}}$, the two-way travel time of nearly 2 s to Moho indicates normal oceanic crustal thickness of about 6 km (Supplementary Fig. 1). There is no indication from available seismic lines that major topography such as stratovolcanoes forms the ASB basement. The floor of the basin is shallower than other basins west of the KPR and the WPB (for example, ref. 10). International Ocean Discovery Program (IODP) Expedition 351 targeted the ASB, anticipating the earliest stages of arc inception and evolution of the northern IBM arc would be preserved in the recovered sedimentary record. The basement composition and age would constrain the petrological, geochemical and tectonic evolution of the arc and subduction zone initiation. By extrapolation of the ASB basement seismic characteristics beneath the KPR, the structure of the IBM arc as a whole could be determined. Before Expedition 351, it seemed that the early ASB sediment and basement might be Palaeogene[20] or even Cretaceous in age. During Expedition 351, IODP Site U1438 (4,700 m water depth) penetrated 1,461 m of sediments and sedimentary rocks and 150 m of the underlying igneous basement of the ASB (Fig. 3). In terms of subduction inception, the nature of the basement and immediately overlying sedimentary rocks are critical and presented here. The results were unexpected, and require reappraisal of the style of arc magmatism immediately following inception, and of the significance of the large volume of subduction-related basaltic crust associated with this intra-oceanic island arc.

The ASB basement and overlying sediments

A rubbly contact is present between overlying brown laminated mudstone and underlying, oxidized basalt. Overall, the ASB basement comprises variably altered and veined, lava sheet flows of sparsely vesicular to non-vesicular, microcrystalline to fine-grained, aphyric to sparsely microphyric, high-Mg, low-Ti, tholeiitic basalts. Phenocrysts are present in ~50% of samples, and consist of plagioclase, clinopyroxene, titanomagnetite and olivine in order of decreasing abundance. Several chilled flow margins are present, but few preserve glassy margins. Petrologic details and representative photomicrographs (Supplementary Fig. 2) are given in the Supplementary Information.

Bulk compositions determined shipboard by inductively coupled plasma atomic emission spectrometry are presented in Supplementary Table 1. The basalts mostly have high MgO (generally >8 wt%), low TiO_2 (0.6–1.1 wt%), low Zr (mostly <50 ppm), high Sc (mostly >40 ppm) and high Cr (up to ~400 ppm). These basalts are compositionally distinct compared with mid-ocean ridge basalts (MORB), but generally similar to the ~48-Myr-old basalts recovered at Site 1201 (Ocean Drilling Program Leg 195) in the West Philippine Basin[21] (Fig. 1), the ~52-Myr-old tholeiitic basalts (termed fore-arc basalts; FAB) recovered from the IBM Trench slope[22–25] (Fig. 1) and recently in the Izu–Bonin fore-arc by IODP Expedition 352 (ref. 26) (Fig. 4 and Supplementary Figs 3 and 4).

The lowermost sedimentary rocks (Unit IV) overlying the basement are clearly critical in terms of the earliest record of adjacent volcanic edifices, such as the developing KPR. Immediately above basement is a 4-m-thick section of dark reddish mudstone and sandstone passing upwards to fine to coarse tuffaceous rocks, and then fine to medium to coarse sandstone and breccia–conglomerate. The lithologic and palaeontologic details are given in the Supplementary Information. A summary biostratigraphic- and palaeomagnetic-based age–depth plot for the sediments at Site U1438 is shown in Fig. 3. On the basis of the biostratigraphic data, the calculated average sedimentation rate for the lowermost 70 m of the supra-basement sediments is between 2 to 14 mm kyr^{-1}, without considering compaction. Allowing for a compaction factor ranging from 3 to 5, the average sedimentation rate would be between 6 to 69 mm kyr^{-1}. On that basis, the minimum age of the uppermost basement is inferred to be between 51 to 64 Myr ago, with a probable age around 55 Myr. Consistent with the biostratigraphic constraints, *in situ* downhole temperature measurements and thermal conductivity measurements on core material to 85 m depth beneath the sea floor give a calculated heat flow of 73.7 mW m^{-2} (Supplementary Fig. 3), implying a thermal age for the underlying lithosphere of 40–60 Myr (ref. 27).

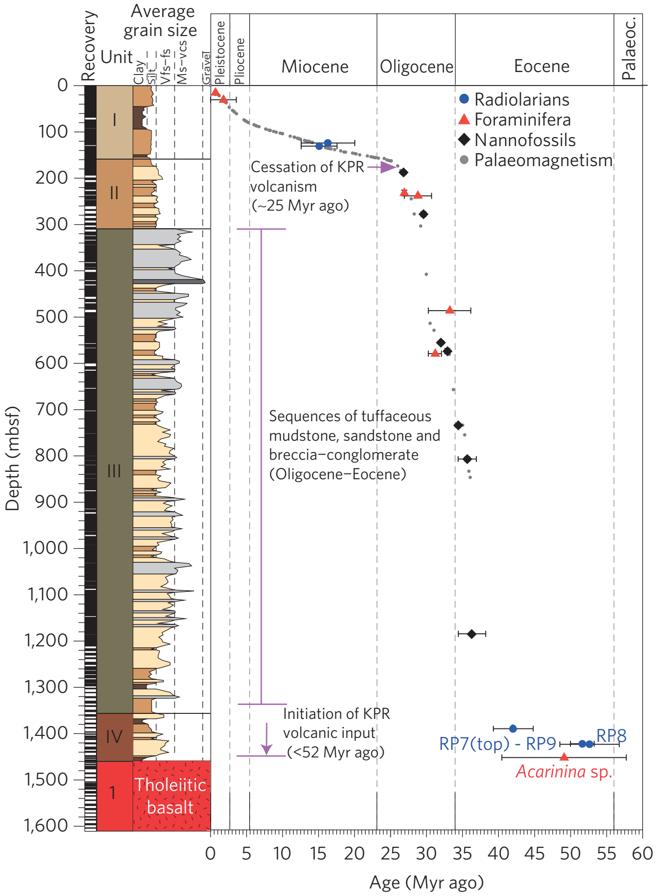

Figure 3 | Graphic lithologic summary, biostratigraphic- and palaeomagnetic-based age–depth plot for IODP Site U1438. Mbsf, metres below sea floor; Vfs–fs, very fine sand–fine sand; Ms–vcs, medium sand–very coarse sand; Palaeoc., Palaeocene. Fossil occurrences are described in the Supplementary Methods. Numbers in the Unit column are lithologic units distinguished on the basis of petrologic characteristics.

Subduction inception and early IBM arc magmatism

Before Expedition 351, we expected ASB basement rocks to be tens of millions of years older than the IBM arc inception date (52 Myr ago according to fore-arc exposures[23]), and potentially bounded on the western margin of the ASB by an old transform fault. Two other assumptions prevailed: the tectonic setting of the basement was assumed to be non-arc-related, given its depth relative to nearby inter-ridge and back-arc basins, and relatively smooth morphology (Fig. 1); and the strike of the KPR stratovolcanic edifices (proto-IBM arc) is subparallel to the nascent

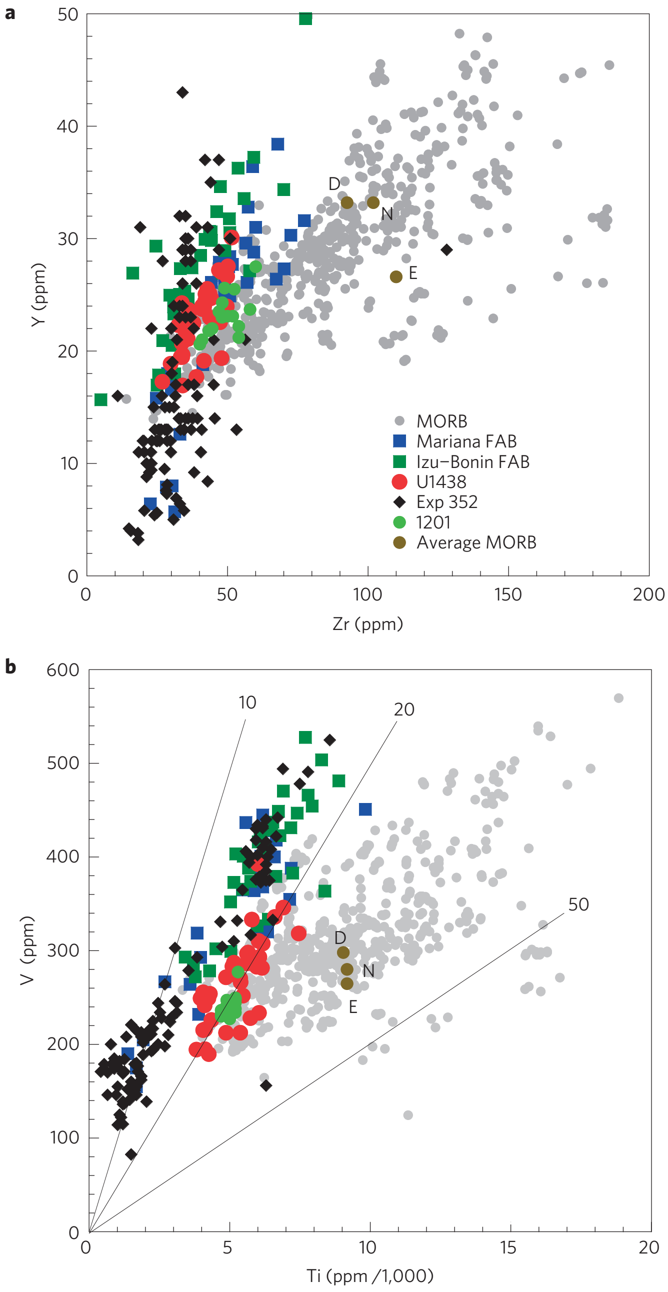

Figure 4 | Comparative geochemical plots of mid-ocean ridge and subduction-related basalts. Comparison of samples from Site U1438 with global MORB (ref. 29), Izu–Bonin–Mariana fore-arc basalts (FAB; refs 23,24), IODP Expedition 352 FAB and boninite[26], Site 1201 (ref. 21), and global MORB averages, with abbreviations: D, depleted; N, normal; E, enriched[43]. **a**, Y versus Zr abundances in basalts, noting high Y/Zr is indicative of derivation of basalt from highly depleted upper mantle sources. **b**, V versus Ti abundances in basalts. Most MORB have 20 < (Ti ppm/1,000)/V ppm <50 whereas tholeiitic basalts in island arcs, including FAB, have (Ti ppm/1,000)/V ppm < 20 (ref. 35). Some boninite from the Izu–Bonin–Mariana arcs have (Ti ppm/1,000)/V ppm < 10 (ref. 26). Further data shown in Supplementary Figs 3 and 4.

IBM trench and at an angle to the bounding features of the ASB or neighbouring Cretaceous-aged arcs, suggesting a locus for initial arc magmatism independent of the immediate ASB basement origins or tectonic setting[10].

Drilling results at Site U1438 have defied expectations, and none of these assumptions now seem valid. There is marked geochemical and petrological equivalence of the igneous basement at sites U1438, 1201 and the FAB of the present-day IBM fore-arc[21–24,26,28]. Compared with MORB (ref. 29), Site U1438 basalts are notable for the presence of phenocryst clinopyroxene (see pyroxene paradox[30,31]), high MgO/FeO, and markedly low TiO_2, low Zr and high Sc abundances. The tholeiitic basalts in both present-day fore-arc and ASB were probably derived from upper mantle sources more strongly depleted in terms of magmaphile trace elements than those typically tapped beneath mid-ocean ridges. The critical distinctive characteristics of these basalt types compared with MORB are their low Zr/Y and Ti/V (Fig. 4). These characteristics relate to the tapping of a more refractory (prior melt-depleted) mantle source and presumably more oxidized melting conditions than those beneath mid-ocean ridges[32–35]. It is noteworthy, however, that the Ti/V of FAB from the IBM fore-arc are lower than those of sites U1438 and 1201, and overlap those of Site A (Fig. 1) in the fore-arc (Supplementary Fig. 4), possibly indicative of decreasing mantle wedge oxidation from trench-proximal to distal across the strike of the nascent IBM arc. Whereas there is muted development of Pb and other fluid-mobile, lithophile trace element spikes[23,24], the involvement of subducted slab-derived fluids in the genesis of FAB is implicated by: the ‘spoon-shaped’ rare-earth-element abundance patterns compared with mid-ocean ridge basalts[29]; the presence of clinopyroxene phenocrysts relating to relative suppression of plagioclase saturation resulting from elevated H_2O contents; and depleted character of the mantle source(s), probably requiring fluid fluxing for melting. Basalts from Site 447 (Fig. 1; on magnetic anomaly 22, ~44 Myr) in the West Philippine Basin have a depleted character similar to FAB (ref. 36), but also normal olivine–plagioclase phenocryst assemblages characteristic of MORB, and lack clinopyroxene, plausibly reflecting low dissolved H_2O contents. The important point is the specific ensemble of petrologic characteristics of FAB is unequivocally related to subduction zone magmatism, albeit at an early stage of development in any given arc setting. We note tholeiitic basalts derived from refractory mantle sources equivalent to those tapped during FAB genesis are being erupted in some active rear-arc settings. For example, those of the Fonualei Rifts adjacent to the northernmost Tonga Arc have strikingly low Zr/Y and Ti/V (10 to 20) equivalent to those of FAB (ref. 37), but are also characterized by more strongly elevated Pb/Ce and other indicators of a larger slab-derived, large-ion lithophile-enriched fluid component in their genesis than FAB.

We conclude on the basis of available age constraints, probable sheet lava flow morphology, petrology and key geochemical characteristics that the basement of the ASB is equivalent to the FAB exposed in the trench slope of the IBM arc. We recognize that radiometric dating of the ASB basement is required, and may temporally have preceded the FAB exposed in the present-day fore-arc. Reconstruction of the nascent IBM arc then implies an across-arc-strike extent for FAB and basement of the ASB of at least ~250 km, after accounting for back-arc extension. The multiple feeder dyke systems of FAB observed in the trench slope are all consistent with an origin for these basalts in a tectonic environment characterized by seafloor spreading. The seismic structure of the KPR indicates the igneous basement at sites 1201 (ref. 38) and U1438 (ref. 39) continues beneath the Ridge, and there is an absence of the thick (>5 km) middle crustal layer with $V_p \sim 6\,\mathrm{km\,s^{-1}}$ (plausibly dioritic) that characterizes the active IBM arc[40]. Sediments overlying the ASB basement contain an increasing volumetric input from adjacent arc edifices, inferred to be the developing stratovolcanoes of the KPR, but possibly from activity on adjacent Daito ridges and Amami Plateau. The KPR volcanoes have no apparent or simple relationship with any of the observable tectonic features of the basement on which they are superimposed. Similar indifference with respect to basement features is manifested globally by many island and continental arc chains of volcanoes. The assumption that the strike of the KPR precludes models of subduction initiation along a pre-existing zone of weakness is erroneous because the local ASB basement (lava flows) was not formed before the development of subduction. In fact, the ASB basement has either blanketed any pre-existing basement or, if formed through seafloor spreading, represents 100% new crust. The evidence that the western boundary of the ASB is a N–S-striking transform fault is not proven, and could postdate, at least in part, formation of the ASB.

An important corollary is much of the areally extensive, basaltic crust of the earliest IBM arc was constructed by subduction-related processes rather than at a pre-∼52 Myr ago mid-ocean ridge. The limited presence of Jurassic (159 Myr ago) arc-type tholeiites in the IBM trench slope[23] is an indication that the ∼52 Myr-old crust developed in rifted older arc basement. Previous attempts at calculating volumetric fluxes in the IBM system have deducted a basement crustal thickness equivalent to that of ordinary, mid-ocean ridge-generated crust[41]; this potentially results in underestimation of the volumetric flux for the early IBM arc, which may have been equivalent for a few million years of early arc growth to that of mid-ocean ridges (∼1,000 km^{3} km^{-1} Myr^{-1}).

Clearly, our general conceptions of the earliest stages of intra-oceanic arc development need substantial modification. Suggestions (for example, ref. 6) that the post-FAB sequences of boninite pillow lava and dyke outcrops at the type locality at Chichijima and at ODP Site 786 (both in the IBM fore-arc) developed in an extensional environment with no localization of archetypal stratovolcano edifices, are confirmed and amplified by the identification of widespread preceding eruptions of tholeiitic basalts. The latter formed the basement on which a restricted across-strike distribution of individual stratovolcanoes was developed, preserved in the remnant arc of the KPR. The apparent absence of boninite lithologies at Site U1438 may reflect a trenchward restriction and focusing of wedge melting as the arc developed.

Overall, it seems major motion changes of the Pacific plate following subduction of the Izanagi–Pacific Ridge along East Asia led to reorganization of equatorially located networks of island arc systems in the region between the Australian and Asian plates[42]. The Philippine Sea plate developed in this region, and experienced trench roll-back at one or more of its bounding plate margins (∼60 Myr ago). Subduction initiation ∼52 Myr ago at the future site of the IBM system, triggered rifting and seafloor spreading of the overriding plate, forming an extensive basaltic arc crust, both along- and across-strike. Localization of a defined chain of stratovolcanoes atop this basement later formed a volcanic front. Areally extensive basaltic crust with unequivocal subduction-zone-related petrological and geochemical signatures is consistent with a spontaneous subduction initiation mechanism[6], but not at a pre-existing fracture zone (for example, ref. 10).

It is still possible the ASB formed through spreading in a marginal basin associated with subduction earlier than IBM inception, but structural relationships of the basin with surrounding ridges do not clearly indicate such an association. Rather than across-strike variation in mantle processes, the additional geochemical data indicate potential along-strike influences. Closure of the Shikoku Basin shows the ASB and site U1438 are conjugate to site A in the IB fore-arc (Fig. 1) whereas Site B, Expedition 352 and the Bonin (fore-arc) Ridge are conjugate to the Daito and Oki-Daito ridges; a greater subduction-related influence on the mantle before IBM inception may be expected for these latter sites, consistent with their lower Ti/V.

Finally, we note a forced subduction initiation is not altogether precluded, because although evidence for a pre-subduction initiation basement is not widespread, it may exist. These uncertainties require resolution by detailed multidisciplinary studies of samples recovered by the triplet of IODP expeditions (350–352) to the IBM system.

Methods

All data generated during IODP Expedition 351 will be publicly accessible from 31 July 2015 via the IODP-JOIDES Resolution Science Operator website (http://www.iodp.tamu.edu).

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Author contributions

All co-authors were participants on IODP Expedition 351 and participated in generating the data published herein, the data analysis and interpretation, and contributed to the writing of this manuscript. Specifically: R.J.A., O.I. and K.A.B. planned and implemented the expedition; A.P.B., P.A.B., R.H.-V., F.J., K.K., Y.K., H.L., K.M.M., A.McCarthy, S.M., I.P.S., F.J.T.III and G.M.Y. generated the lithologic data; M.H.J., A.N.B.-M., R.d.M.G. and S.K. performed the biostratigraphy; M.M. and A.Morris performed the magnetostratigraphy; L.D., M.G., M.H. and M.N. calculated the thermal age of basement; and L.C.L., C.S., C.v.d.L. and Z.Z. generated the geochemical data.

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 R.J.A.

Competing financial interests

The authors declare no competing financial interests.

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