Earth's youngest known ultrahigh-temperature granulites discovered on Seram, eastern Indonesia

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ABSTRACT

Episodes of ultrahigh-temperature (UHT, ≥900 °C) granulite metamorphism have been recorded in mountain belts since the Neoarchean. However, evidence for the tectonic mechanisms responsible for the generation of such extreme thermal conditions is rarely preserved. Here we report the discovery of 16 Ma UHT granulites—the youngest identified at the Earth's surface—from the Kobipoto Mountains of Seram in eastern Indonesia. UHT conditions were produced by a modern tectonic system in which slab rollback–driven lithospheric extension caused core complex–style exhumation of hot subcontinental lithospheric mantle. Overlying continental crust, heated and metamorphosed by exhumed lherzolites, developed spinel + quartz and sapphirine-bearing residual assemblages, shown by phase equilibria modeling to have required temperatures of ~950 °C at ~8 kbar pressure. Seram is therefore a possible modern analogue for ancient orogens that incorporate UHT granulites.

INTRODUCTION

Ultrahigh-temperature (UHT) metamorphism of Earth's crust, at ≥900 °C and moderate (~7–13 kbar) pressure (Harley, 2008; Kelsey, 2008), has been a feature of the rock record since the Neoarchean and has been identified at ~50 localities (Brown, 2006; Kelsey, 2008); however, there is no general consensus for the tectonic mechanisms to account for it (e.g., Kemp et al., 2007; Clark et al., 2011). In the modern Earth, extremes of thermal metamorphism have been identified deep in the Tibetan crust (Hacker et al., 2000), but replicating such high temperatures in mountain belts using numerical models has proved challenging except when extension is invoked (Schenker et al., 2012).

Tectonic scenarios hypothesized to have generated UHT conditions in older orogens include heating by continental backarc extension (e.g., Kemp et al., 2007) and subsequent hot backarc thickening (Brown, 2006); thickening of crust primed by melt extraction during earlier episodes of anatexis (Clark et al., 2011); and orogenic self-heating by radioactive elements (Clark et al., 2011) and/or by viscous strain heating (Nabelek et al., 2010). However, it has often proved difficult to apply such geodynamic models to Archean and Proterozoic UHT belts that either have been overprinted by subsequent orogenic cycles or that no longer preserve the geological conditions that once drove UHT metamorphism. Here we describe a unique example of modern UHT metamorphism for which the tectonic driver is evident from geological field observations (Pownall et al., 2013) and can be related to present-day subduction dynamics (Spakman and Hall, 2010).

GEOLOGY OF SERAM

Eastern Indonesia (Fig. 1A) is an actively deforming and tectonically complex region controlled by the ongoing collision between the Eurasian, Australian, and Philippine Sea plates (Hall, 2012). The island of Seram (Fig. 1B), in the northern limb of the Banda Arc (Fig. 2D), exposes widespread peridotites that are associated with Miocene–Pliocene cordierite-garnet migmatites and granites and Barrovian-style metamorphic rocks (Audley-Charles et al., 1979; Priem et al., 1978; Linthout and Helmers, 1994; Honthaas et al., 1999; Pownall et al., 2013). The peridotites have previously been interpreted as remnants of an extensive ophiolite (Monnier et al., 2003) obducted from the south during arc-continent collision, which generated the cordierite granites by subophiolite anatexis within a metamorphic sole (Linthout and Helmers, 1994). However, recent field work (Pownall et al., 2013) on the islands of Seram and Ambon has instead shown that the migmatites, granites, and peridotites (mainly spinel lherzolites) compose a migmatitic-ultramafic core complex, the Kobipoto Complex, that was exhumed at high temperatures beneath a series of low-angle detachment faults, resulting in extensive shearing and localized anatexis of schists and amphibolites within the hanging wall (Fig. 2E). Therefore, the lherzolites are interpreted as subcontinental lithospheric mantle rather than part of an ophiolite; this is supported by the absence of other components of an ophiolite except for scarce gabbros, and large positive gravity anomalies recorded in the vicinity of the peridotites that cannot be accounted for by a thin ultramafic sheet (Milsom, 1977). In central Seram, the major left-lateral strike-slip Kawa shear zone (Pownall et al., 2013; Fig. 1B) incorporates thin slivers of serpentinized peridotites, suggesting that it reactivated lithospheric detachment faults similar to those in western Seram (see Fig. 2E).

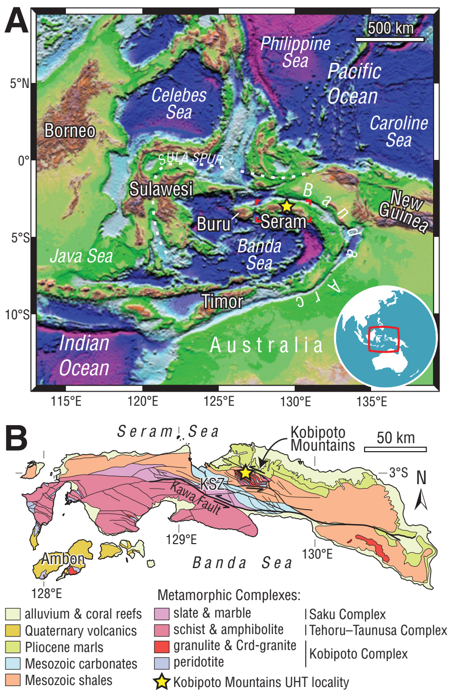

Figure 1. A: Topographic and bathymetric map of eastern Indonesia and surrounding region. B: Geological sketch map of Seram (adapted from Pownall et al., 2013). KSZ—Kawa shear zone; UHT—ultrahigh temperature.

KOBIPOTO COMPLEX GRANULITE PHASE EQUILIBRIA MODELING

River traverses undertaken through dense rainforest of the Kobipoto Mountains in central Seram (Audley-Charles et al., 1979; Pownall et al., 2013) revealed that the peridotites are intimately associated with a granulite facies migmatite complex incorporating (1) metatexites with Al-Fe–rich garnet-sillimanite-cordierite-spinel (Grt-Sil-Crd-Spl) residua (Figs. 3B and 3F); and (2) granitic diatexites (described previously as cordierite granites), which host abundant millimeter-scale Spl + Sil schlieren, and peritectic Crd and Grt (migmatite terminology follows Sawyer, 2008). A Grt-Sil-Crd-Spl metatexite granulite boulder (sample KP11-588; Fig. 3) with a highly aluminous (28.07 wt% Al_2O_3) and iron-rich (13.25 wt% FeO + Fe_2O_3) metapelitic composition was collected from the Wai Tuh river gorge (129.479°E, 3.002°S).

Abundant (~25 vol%) almandine-rich garnets (≤4 mm diameter) are separated from large swathes of embayed prismatic sillimanite by layered symplectic coronae comprising a Crd ± Qz (quartz) ± Pl (plagioclase) layer adjacent to garnet, and a Crd + Spl + Ilm (ilmenite) ± Crn

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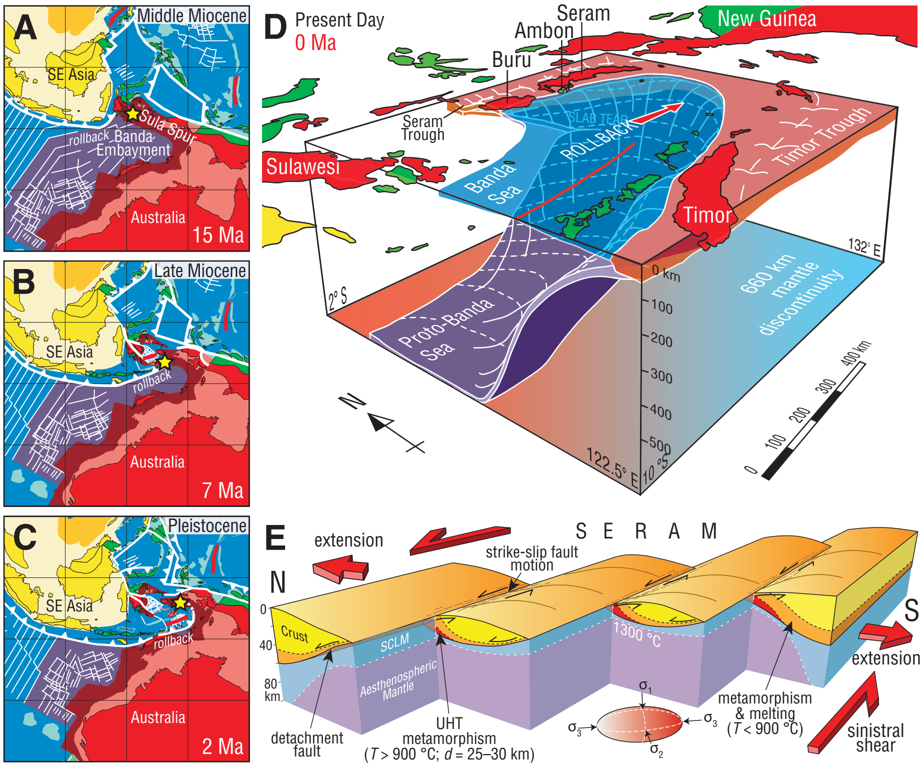

Figure 2. Reconstructions of eastern Indonesia, adapted from Hall (2012), depict collision of Australia with Southeast Asia and slab rollback into Banda Embayment. Yellow star indicates Seram. Oceanic crust is shown in purple (older than 120 Ma) and blue (younger than 120 Ma); submarine arcs and oceanic plateaus are shown in cyan; volcanic island arcs, ophiolites, and material accreted along plate margins are shown in green. A: Reconstruction at 15 Ma. B: Reconstruction at 7 Ma. C: Reconstruction at 2 Ma. D: Visualization of present-day slab morphology of proto–Banda Sea based on earthquake hypocenter distribution and tomographic models (see Pownall et al., 2013, and references therein). E: Schematic block model (effectively north-south cross section through Seram) demonstrating generation of ultrahigh-temperature (UHT) conditions (red) in crust by extreme extension accommodated by lithospheric detachment faults and their subsequent strike-slip reactivation. Indicated depth (*d*) of UHT metamorphism is based on pressure of 8 kbar (indicated in Fig. 3A). Strain ellipsoid is schematic. SCLM—subcontinental lithospheric mantle; *T*—temperature.

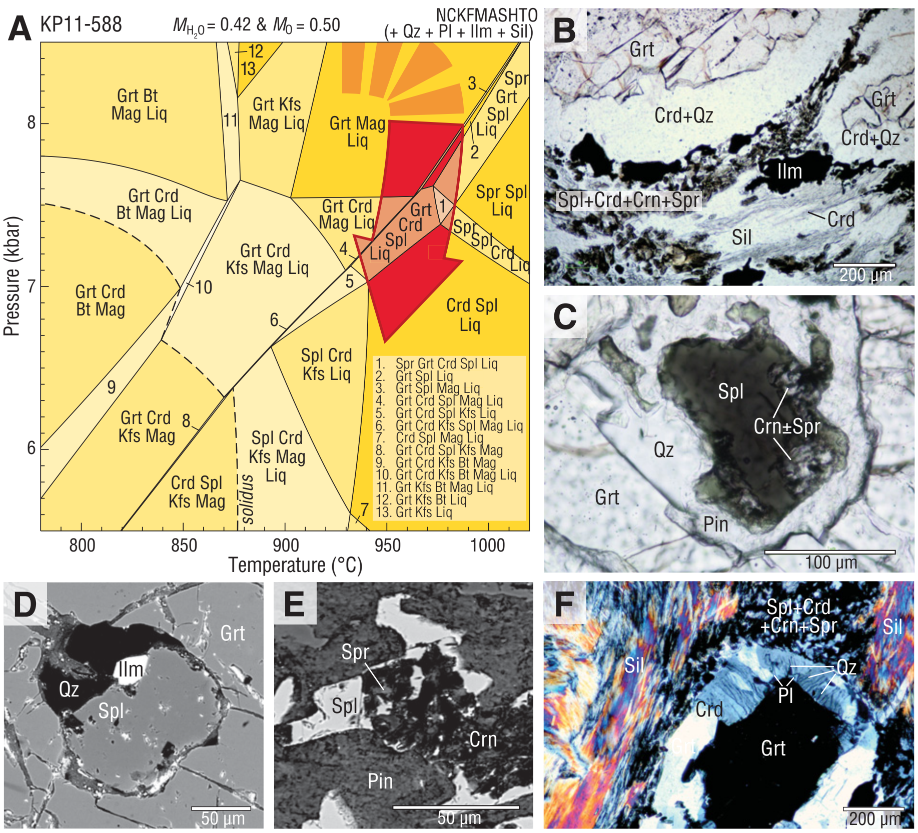

Figure 3. A: Pressure-temperature (*P-T*) pseudosection of granulite KP11-588, calculated using THERMOCALC (Powell and Holland, 1988) in the NCKFMASHTO (Na_2O-CaO-K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O-TiO_2-Fe_2O_3) chemical system using H_2O abundance (M_{H_2O}) and M_O values of 0.42 (Fig. DR2; see footnote 1) and 0.50 (see Fig. DR3), respectively. Assemblage Qz + Pl + Ilm + Sil is common to all fields. Mineral abbreviations: Bt—biotite; Crd—cordierite; Crn—corundum; Grt—garnet; Ilm—ilmenite; Kfs—K-feldspar; Liq—silicate melt; Mag—magnetite; Pin—pinite (after Crd); Pl—plagioclase; Qz—quartz; Spr—sapphirine; Sil —sillimanite; Spl—spinel. B: Ordered reaction structures of Crd + Qz coronae and Spl + Crd + Ilm (± Crn ± Spr) symplectite separating Grt from Sil (plane-polarized photomicrograph) were formed by near-isothermal decompression from peak *P-T* conditions of ~950–990 °C and ~8 kbar (shown in A by red arrow). C, D: Spl + Qz (± Ilm ± Crn ± Spr) inclusions within garnet (C—plane-polarized photomicrograph; D—backscattered electron image) are characteristic of ultrahigh-temperature metamorphism. E: Sapphirine (shown also in C) (backscattered electron image), now mostly altered to Crn + Chl, if it was once stable with Qz, would have required $T > 970$ °C, as modeled in A. F: Cross-polarized photomicrograph of reaction textures between Grt and Sil showing vermicular Qz intergrowths and Pl in Crd corona.

(corundum) ± Spr (sapphirine) layer adjacent to sillimanite (Figs. 3B and 3F). Sillimanite is interpreted to be mostly pseudomorphs after kyanite. Pyroxene and K-feldspar are absent. Minor (~10 vol%) quartz-bearing leucosomes occur as millimeter-scale segregations. Extremely small (≤10 μm) blebs of variably chloritized sapphirine occupy embayments within corundum, both in the symplectic coronae (Fig. 3E) and in composite inclusions within garnet (Fig. 3C), and have compositions that show retrograde alteration to the enveloping corundum and chlorite (cf. Seifert, 1974): analyses of all these phases plot on a mixing line that intersects the $2MgO{:}2Al_2O_3{:}SiO_2$–$3MgO{:}5Al_2O_3{:}SiO_2$ ideal sapphirine solid solution (Fig. DR1 in the GSA Data Repository[1]).

Aside from cordierite, small biotite grains occurring as scarce inclusions within garnet represent the only hydrous phase, indicating a notably dry composition for the rock. This is corroborated by temperature versus H_2O abundance (T–M_{H_2O}) pseudosection modeling of the residuum using THERMOCALC 3.33 software (Powell and Holland, 1988; see the methods discussion and Fig. DR2 in the Data Repository) in which calculated equilibria indicate a low H_2O content of ~0.4 wt%, likely achieved by the extraction of hydrous silicate melt produced by muscovite- and biotite-consuming prograde reactions (cf. White and Powell, 2002).

Spinel and quartz, occurring with ilmenite as inclusions within garnet, thus likely belonging to the prograde assemblage, are found either in direct grain contact (Fig. 3D) or separated by a thin reaction rim of plagioclase or cordierite (Fig. 3C). Coexisting Spl + Qz is considered possibly indicative of UHT conditions and has been reported from many well-studied HT and UHT localities (e.g., Waters, 1991). Although Spl + Qz stability may extend to sub-UHT temperatures at low pressure (P < ~5.5 kbar; Kelsey et al., 2004) or through incorporation of ZnO, Cr_2O_3, and/or Fe_2O_3 into spinel (Waters, 1991), the Spl + Qz assemblage shown here is considered a relatively robust UHT indicator. The ZnO content of the hercynite spinel ranges between 0 and 2.2 wt% (1.1 wt% average), the Cr_2O_3 content is negligible, and the rock is shown to have equilibrated at a moderate XFe^{3+} (Fe^{3+}/Fe^{total}) value of ~0.3, as determined from temperature versus oxygen content (T–M_O) pseudosection modeling (see the methods and Fig. DR3 in the Data Repository). Furthermore, P is constrained to >7 kbar by the phase equilibria modeling discussed herein.

Spr + Qz is widely regarded as diagnostic of UHT metamorphism (Kelsey et al., 2004; Harley, 2008; Kelsey, 2008) for all but highly oxidized rocks (Taylor-Jones and Powell, 2010); however, it is not clear in this instance if the sapphirine ever coexisted with quartz. The two phases, which together compose only a small fraction of the residual assemblage, occur in the same inclusions (e.g., Fig. 3C) but are not observed in direct grain contact. Alternatively, sapphirine may have formed at lower T than the Spr + Qz stability field by localized reactions involving spinel and cordierite (e.g., Hensen and Green, 1971; Seifert, 1974).

Ordered reaction structures involving cordierite- and spinel-bearing symplectite produced by the breakdown of garnet (Figs. 3B and 3F) are characteristic of formation by near-isothermal decompression (Harley, 1989). These coronae most likely formed by the generalized continuous reaction Grt + Sil → Spl + Crd + Qz, which was calculated by Kelsey et al. (2004) in the FeO-MgO-Al_2O_3-SiO_2 (FMAS) chemical system (Hensen and Green, 1971) to occur between 900 °C (at 5.2 kbar) and 990 °C (at 6.6 kbar). Quantitative constraints on the pressure-temperature (P-T) evolution use a pseudosection calculated using THERMOCALC 3.33 in the Na_2O-CaO-K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O-TiO_2-Fe_2O_3 (NCKFMASHTO) chemical system for the bulk rock composition of the granulite (Table DR1 in the Data Repository) utilizing the previously determined H_2O and O contents. The P-T pseudosection (Fig. 3A) shows a narrow region in which garnet and spinel stably coexist (equivalent to the reaction Grt + Sil → Spl + Crd + Qz) that extends from ~820 °C (at 5.5 kbar) to ~1020 °C (at 8.3 kbar). The fine-grained nature of the Crd + Spl symplectites replacing garnet suggests that these fields were crossed by moving down P as opposed to up T (cf. Harley, 1989). A lower T limit of ~940 °C for this part of the P-T path is delimited by the extent of the K-feldspar–absent fields through which the rock must have passed (Fig. 3A). If sapphirine and quartz did coexist, this T estimate would be raised to >975 °C. These requirements permit a clockwise P-T path with a metamorphic peak at ~950–990 °C at ~8 kbar (Fig. 3A), implying an apparent geothermal gradient of ~120 °C kbar^{-1} (~35 °C km^{-1}) around the peak of granulite facies metamorphism.

GEOCHRONOLOGY

Cordierite diatexites and associated granites occurring within exhumed lherzolites in western Seram and on Ambon (Pownall et al., 2013) have been dated as Miocene–Pliocene in age (Priem et al., 1978; Honthaas et al., 1999), and ambonites (Crd + Grt dacites sourced from the Kobipoto Complex migmatites and erupted on Ambon; Pownall et al., 2013) are as young as 2 Ma (Honthaas et al., 1999), but the granulites present in the Kobipoto Mountains have not previously been dated.

U-Pb Zircon

Zircons separated from metatexite residuum (KP11-588), biotite-bearing diatexite melanosome (KP11-619), and cordierite diatexite leucosome (KP11-621) found as boulders in the Wai Tuh were analyzed for U, Th, and Pb using a sensitive high-resolution ion microprobe (SHRIMP). A narrow (<20 μm) O_2^- ion beam was used to target both thick (often >20 μm) high-U (and low Th/U) metamorphic rims and complexly zoned xenocrystic cores of single grains. Consistent and concordant mean $^{206}Pb/^{238}U$ ages of 15.77 ± 0.24 Ma (KP11-588; Fig. 4), 16.00 ± 0.52 Ma (KP11-619; Fig. DR4), and 16.24 ± 0.23 Ma (KP11-621; Fig. DR5) were calculated for the zircon rims, and Paleoarchean to Paleozoic U-Pb ages (from 3416 ± 8 Ma) were calculated for the inherited cores (Table DR2). The Kobipoto Complex migmatites do not show evidence of a metamorphic or metasomatic overprint after granulite facies metamorphism; the Miocene zircon rims therefore are interpreted to have grown during the UHT event.

$^{40}Ar/^{39}Ar$ Biotite

Biotite from the melanosome (KP11-619), which likely formed by diffusive transfer of H_2O from the melt during high-T retrogression (cf. White and Powell, 2010), is shown by $^{40}Ar/^{39}Ar$ furnace step-heating geochronology to record the low-T cooling history through ~290 °C at 16.34 ± 0.04 Ma, and later through ~230 °C at 14.83 ± 0.29 Ma at an average rate of ~40 °C m.y.$^{-1}$ (following the method of Forster and Lister, 2004; see Table DR3 and Figs. DR6–DR9). The low-T 16.34 ± 0.04 Ma Ar-Ar age overlaps (within analytical error) the 16.00 ± 0.52 Ma high-T SHRIMP $^{206}Pb/^{238}U$ zircon age for the same rock, thus suggesting that an initial

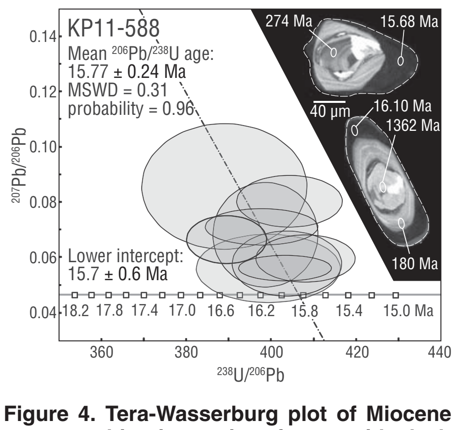

Figure 4. Tera-Wasserburg plot of Miocene metamorphic zircon rims from residual ultrahigh-temperature granulite sample KP11-588. Mean $^{206}Pb/^{238}U$ age is quoted at 95% confidence. Data-point error ellipses are drawn at 68.3% confidence. MSWD—mean square of weighted deviates. Representative cathodoluminescence images of zircon grains are shown at top right, annotated with individual analytical spots. See Table DR2 (see footnote 1) for full data set.

[1]GSA Data Repository item 2014105, methods, Tables DR1–DR6, and Figures DR1–DR9, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

period of exceptionally rapid cooling caused by rapid exhumation of the Kobipoto Mountains must have followed the near-isothermal decompression stage shown in Figure 3A.

TECTONIC MECHANISM FOR MODERN (16 Ma) UHT METAMORPHISM

The occurrence of voluminous spinel lherzolites in contact with the Kobipoto Complex migmatites strongly suggests that juxtaposition of hot (~1300 °C) subcontinental lithospheric mantle against the mid-crust drove UHT metamorphism on Seram (Fig. 2E). A major extensional episode is interpreted to have initially exhumed the subcontinental lithospheric mantle to 25–30 km depth, where UHT metamorphism occurred, resulting in an extremely high heat flow that surpassed that of typical "hot crust" core complex scenarios (cf. Whitney et al., 2013).

The requirement that Seram underwent a period of extreme extension ca. 16 Ma lends strong support to theories of Banda Arc evolution that involve subduction rollback (Figs. 2A–2D). Recently updated plate reconstructions of Southeast Asia (Spakman and Hall, 2010; Hall, 2012) demonstrate that rollback of a single slab into the Jurassic oceanic Banda Embayment had initiated adjacent to the southeast part of the island of Sulawesi before 15 Ma (Fig. 2A), thereby locating Seram in its vicinity at that time. As rollback propagated eastward into the embayment (Figs. 2A–2C), extending and fragmenting the Australian Sula Spur of which Seram is part (Spakman and Hall, 2010), the mantle was rapidly exhumed beneath Seram, inducing melting and UHT metamorphism, as shown here, at 16 Ma. Later, major left-lateral transpressional deformation that formed the Kobipoto Mountains (Pownall et al., 2013) evidently caused further exhumation of the Kobipoto Complex in central Seram and accommodated the final stages of the island's eastward migration (Fig. 2E).

Seram is important in that it exposes hot granulites that formed in a contemporary tectonic setting (see also the Hidaka granulites, Japan; Kemp et al., 2007). The 16 Ma Kobipoto Complex granulites demonstrate that UHT conditions can be produced in the modern plate tectonic regime by slab rollback–induced lithospheric extension, thereby offering one possible solution to the generation of UHT rocks in Neoproterozoic and Phanerozoic orogens for which the original tectonic settings remain unknown.

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