Rapid recycling of subducted sedimentary carbon revealed by Afghanistan carbonatite volcano

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The fate of carbon subducted to mantle depths remains uncertain, yet strongly influences the distribution of terrestrial carbon on geologic timescales. Carbon fluxes into subduction zones are exceptionally high where downgoing plates contain thick sedimentary fans. This study uses volcano geochemistry to assess sedimentary carbon recycling in the high-flux Makran subduction zone, where the Arabian plate subducts northward beneath Eurasia. Based on strontium isotope geochemistry and ^{40}Ar-^{39}Ar geochronology, I show that a portion of the submarine Indus Fan entered the Makran trench, melted, and ascended as magmas that erupted in southern Afghanistan. The resulting volcano—composed primarily of carbonate minerals—formed at approximately 3.8 million years ago. The ^{87}Sr/^{86}Sr of the lavas indicates that their magmatic precursors derived from marine sediments deposited at 28.9 ± 1.4 Ma. This implies that sedimentary carbon subducted to and returned from mantle depths in less than 27 million years, indicating that magmas can efficiently recycle sedimentary carbon from subducting slabs to the overlying plate.

The efficiency of carbon recycling in subduction zones has profound implications for Earth's climate[1]. Some fraction of the carbon entering subduction zones is released from subducted slabs via mechanical removal, metamorphic decarbonation, and melting. The remainder recycles to lithospheric reservoirs in buoyant diapirs[2] and melts[3,4] or enters the convecting mantle[5]. Subducted carbon that does not return to near-surface reservoirs may remain isolated from the biosphere for billions of years[6,7]. Globally, the carbon flux into subduction zones appears to exceed the combined outputs from arc volcanoes and diffuse venting[6,8]. This may be indirect evidence that deep Earth reservoirs serve as carbon sinks on geologic timescales. Yet, the fate of deeply subducted carbon remains an enigmatic aspect of the global carbon cycle.

The Makran subduction zone, with the highest carbon flux per unit length along trench of any modern subduction zone[9], is uniquely well suited for investigating carbon recycling in a high-flux setting. The Makran continental margin is dominantly accretionary[10] and includes a Neogene-Quaternary volcanic arc that consists of three volcanic centers in Iran and Pakistan[11]. Here I present evidence that a carbonatite volcano in southern Afghanistan is a hitherto unrecognized eastern limb of the Makran volcanic arc. This volcano is proof that carbonatitic melts—theoretically generated in subduction zones at postarc depths (>140 km)[6,12], but seldom attributed to volcanic arc processes[13]—can be voluminous enough to efficiently recycle subducted sedimentary carbon to the lithosphere. Isotope geochemistry and geochronology constrain the timing of sedimentary deposition and eruption, respectively, and imply that subducted carbon can return to shallow reservoirs on much shorter timescales than previously thought[14–16].

The Makran subduction zone and volcanic arc

As the Eurasian and Arabian plates converge, Arabian oceanic crust enters the Makran subduction zone at a rate of approximately 30 mm/yr[17]. The Arabian Plate carries Indus Fan sediments—the thickest sequence of sediments (5–7.5 km) entering any subduction zone—into the Makran trench, causing an unusually shallow grade of subduction and an exceptionally large accretionary prism[18]. The crustal wedge extends ~300 km north from the trench, increasing in age from unconsolidated Quaternary sediments through imbricated Miocene ophiolites and metasediments[10].

As previously defined, the Makran volcanic arc consists of three Miocene-Quaternary volcanic centers—Bazman, Taftan, and Koh-i-Sultan—along an east-northeast linear trend oblique to the trench (Fig. 1)[11]. Lavas erupted at these locations have basaltic to rhyolitic compositions and fall along calc-alkaline differentiation trends[19]. Subduction zone geometry varies from east to west: subduction in the east is shallower near the coast[20] and steeper at greater depths[21] compared to subduction in the west. This asymmetry might be due to oceanic lithosphere subduction in the east and continental lithosphere underthrusting in the west[22].

The Khanneshin carbonatites (Extended Data Fig. 1) erupted through Neogene sedimentary rocks (Extended Data Fig. 2) of the Sistan Basin, southern Afghanistan, along intersecting regional faults[23]. The core of the 4-km-wide main vent consists of calcite-rich medium- to coarse-grained carbonatite (sövite) ringed by agglomeritic ankerite-barite carbonatite (Extended Data Figs. 3–5)[24]. Both units contain abundant mica-rich xenoliths of metasomatized wall rock (fenite) and are crosscut by fine-grained carbonatite (alvikite) dikes. A volcano-sedimentary apron extends radially 3–5 km from the main vent and is intruded by many late-stage dikes and volcanic plugs, the youngest of which are phonolitic. Aeromagnetic surveys suggest that as many as eight other minor alkaline igneous centers with unknown ages and compositions may be buried beneath

Holocene sands[23]. Unlike most volcano-forming carbonatites[25], however, the Khanneshin volcano does not appear to be accessory to silicic volcanism.

Chronologic and geochemical constraints

Some geochemical data exist for the Khanneshin carbonatites[23,26,27]. This study adds two critical results: ^{40}Ar-^{39}Ar geochronology that establishes the timing of Khanneshin volcanism and strontium isotopic constraints for Khanneshin rocks (see Supplementary Information for sample descriptions).

^{40}Ar-^{39}Ar geochronology: Sövite sample RT-10K-09—inferred to be the least geochemically evolved because it has light carbon, oxygen, and thallium isotopic compositions[27]—was selected to represent the main stage of eruption. Unlike other mica-bearing Khanneshin samples, the coarse-grained phlogopite in RT-10K-09 is not associated with fenite xenoliths. Step heating experiments on three phlogopite aliquots yielded $^{40}Ar/^{39}Ar$ plateau ages of 3.54, 3.74, and 3.83 Ma that consisted of 63, 45, and 35 percent of the total ^{39}Ar released, respectively (Extended Data Figure 6). Analytical uncertainty for each date is 0.02–0.04 Ma and the full external uncertainty for each analysis is 0.20 Ma. All three $^{40}Ar/^{39}Ar$ ages agree within uncertainty and could represent a single Ar closure age between 3.74 and 3.63 Ma. Alternatively, the oldest date (3.83 Ma) may represent the eruption age of the sövite if the younger dates record partial resetting caused by subsequent eruptive episodes that reheated the sample and caused Ar loss.

Strontium isotopes: Twenty Khanneshin carbonatites have relatively homogenous $^{87}Sr/^{86}Sr$, ranging from 0.707919 ± 7 (RT-11K-06) to 0.708061 ± 8 (KHAN-3) and with a mean of 0.708004 ± 36 (1s, n=20 rocks). This is comparable to previous results for Khanneshin rocks[26] and confirms that there is little Sr isotopic variability across the central vent of the volcano. The brecciated sandstone (represented by sample FH-10K-10) through which the carbonatitic lavas erupted has $^{87}Sr/^{86}Sr$ indistinguishable from the carbonatites; this value probably represents the isotopic composition of calcite veins (Extended Data Fig. 2) rather than the sedimentary protolith (see Supplementary Information).

Evidence for rapid carbon recycling

Three lines of evidence indicate that the Khanneshin magmas were products of active subduction. First, the Khanneshin volcano is spatially and temporally associated with the Makran volcanic arc. Earthquake focal mechanisms within the subducting slab (Fig. 1) extend to 157 km depth[17] and the deepest earthquake occurred less than 70 km to the S-SE of the Khanneshin volcano[28]. This suggests that the slab passes beneath the volcano ~700 km north of the trench at a depth of ~180 km. The age of the Khanneshin volcano is bracketed by silicic volcanism at Bazman (4.6 to <0.6 Ma), Taftan (6.95 to <0.71 Ma), and Koh-i-Sultan (<2.5 Ma) volcanoes[29], which are indisputably part of the Makran volcanic arc. Furthermore, the Khanneshin volcano is only slightly north of the linear trend defined by the other volcanoes (Fig. 1). These observations suggest that that the Khanneshin volcano is the easternmost manifestation of the Makran volcanic arc.

Second, sediments on the downgoing slab beneath the Khanneshin volcano could be fertile sources of carbonatitic melt. In the Makran subduction zone, the slab-mantle interface may not heat to 450 °C until reaching a depth of 75 km[30]. Heating may accelerate as the slab passes through the lithosphere-asthenosphere boundary, located ~150 km beneath the Khanneshin volcano[31]. When heated above ~700 °C, sediment layers thicker than 1 km are prone to forming buoyant diapirs[2], which undergo partial melting and efficient decarbonation as they ascend into the mantle wedge[32]. Sediments can also be convectively transferred from the slab into the mantle wedge[3]. During burial, subducted Indus Fan material (calcareous ooze and clay-rich terrigenous turbidites[33]) would have consolidated and metamorphosed into carbonated pelites. At 950–1050 °C and 3–5 GPa[3,34], these lithologies can produce carbonated alkali-rich melt. Such conditions are plausible near the top of the subducting slab and in the mantle wedge. Carbon- and alkali-rich melt released from metasediments may separate into immiscible carbonatitic and silicate magmas during ascent. The buried igneous centers near the Khanneshin volcano[23] could represent conjugate silicate magmas. Thus, there are viable mechanisms by which carbonatitic melt might be generated beneath the Khanneshin volcano. Exceptionally high rates of carbonatitic melt generation in the Makran subduction zone could be facilitated by (i) an abnormally high sediment flux, (ii) the abundant carbonate in the sediments (they can contain >50% $CaCO_3$[33]) and (iii) efficient carbon subduction past typical forearc depths[9].

Third, the Khanneshin lavas contain geochemical evidence of crustal recycling. Their trace element patterns are consistent with the immiscible separation of carbonatitic magma from silicate magma derived from the melting of Indus Fan material (see Supplementary Information and Extended Data Fig. 7). Isotopically, Khanneshin, Bazman, and Taftan volcanic rocks fall along a common $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ trend (Fig. 2) that diverges from trends attributable to the magmatic fractionation of Rb/Sr and Sm/Nd. Such Sr-Nd decoupling has long been viewed as evidence of sedimentary recycling[35]. The Makran arc values (including the Khanneshin lavas) fall within the Enriched Mantle 2 array, which is likewise attributed to a recycled sediment component[36]. Thallium isotope compositions of Khanneshin lavas also attest to ocean crust recycling, despite being strongly influenced by wall rock interactions[27]. Interestingly, the $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ (18.9, 15.6, and 40.0, respectively) of Khanneshin carbonatites[26] are very similar to average Indus River K-feldspars[37]; Khanneshin lavas may have inherited this signature from continental detritus transported by the Indus River.

Elsewhere, carbonatites may contain ancient recycled material from lithospheric reservoirs reactivated by backarc extension, mantle wedge flow, or ascending magmas. That is not a likely source of the recycled sedimentary component in the Khanneshin lavas. The Afghan block, through which Khanneshin magmas erupted, formed by the accretion of one or more Gondwana microcontinents to Asia by the Early Cretaceous[38]. Southern Afghanistan, as part of the vast Alpine-Himalayan orogen, should have young lithospheric mantle (probably less than 50 Ma[39]) and is far from cratons that could serve as long-lived geochemical reservoirs. Thus, and for the reasons outlined above—(i) spatiotemporal associations with arc volcanism and the Makran slab, (ii) viable mechanisms for voluminous carbonatitic melt production, and (iii) geochemical evidence for recycled sedimentary material—Khanneshin carbonatites can be viewed as products of Makran subduction.

Sediments in the Makran subduction zone are the most likely source of Khanneshin magmas. Because Khanneshin lavas have very high Sr concentrations (multiple wt% in most cases), substantial Sr isotopic contamination during magma ascent seems unlikely, even if Paleozoic or older rocks exist beneath the volcano. As noted above, the mantle lithosphere beneath the volcano is young, so remobilization of Sr implanted in the subcontinental lithosphere prior to the initiation of the Makran subduction zone also seems unlikely. Instead, the $^{87}Sr/^{86}Sr$ measured in Khanneshin rocks probably reflects the isotopic composition of subducted Indus Fan material. The Indus River initiated during the Eocene shortly after the India-Asia collision began and much of the fan appears to be Paleogene[40]. If the Khanneshin lavas inherited the $^{87}Sr/^{86}Sr$ of their sedimentary precursors, the monotonic increase in marine sedimentary carbonate $^{87}Sr/^{86}Sr$ since 40 Ma can be used as a chronometer (Fig. 3). Average marine carbonates[41] have $^{87}Sr/^{86}Sr$ overlapping with mean Khanneshin carbonatites (0.708004 ± 36) only once since 200 Ma. The $^{87}Sr/^{86}Sr$ range in Khanneshin lavas suggests that their source rocks had a mean deposition age of 28.9 ± 1.4 Ma, which coincides with early Indus Fan growth. Assuming that $^{40}Ar/^{39}Ar$ plateau ages (3.83–3.54 Ma) record the main stage of volcanism, 24–27 Myr passed between deposition and eruption. The current length of the slab from the trench to beneath the volcano is ~700 km. However, the trench has migrated 140 km southward since the mid-Miocene[42], so the slab segment currently beneath the volcano traveled only ~560 km since entering the trench. At the current rate of 32.6 mm/yr[17], subduction to beneath the Khanneshin volcano would take 17 Myr. Thus, sediment transfer to the trench and the ascent of recycled materials from the slab presumably lasted <10 Myr combined.

Recycled carbon resides in continental carbonatites

There is increasing isotopic evidence that some carbonatitic magmas worldwide contain recycled crustal material. Radiogenic isotope systematics suggest that carbonatites derive from either marine sedimentary carbon recycled through subcontinental lithosphere or deeply subducted carbonated oceanic crust that returns from either the transition zone or from the core-mantle boundary[14]. The role of recycling is confirmed by calcium isotopes[16] and boron isotopes[15], but the recycling scenarios invoked by these studies require timescales of 100–1000 Myr. The Khanneshin volcano is evidence that sedimentary carbon recycles to and from typical postarc depths on short timescales (i.e., <100 Myr). Low-volume carbonatitic melts cannot survive metasomatic entrapment[43] and rapid devolatilization[44] during ascent, so the exceptionally high sedimentary carbon flux into the Makran trench may have been necessary to produce carbonatitic magmas voluminous enough to reach the surface. This might explain why carbonatite volcanism occurs in the Makran subduction zone, but not elsewhere on Earth[13].

Globally, subducting carbon inputs appear to be larger than volcanic arc outputs[6,8]. This imbalance is especially pronounced for the Makran and Andaman-Burma subduction zones, where the Himalaya-derived Indus and Bengal fans may transport >12 Mt/yr of carbon—roughly 7% of the global subducting carbon flux[1]—into the mantle wedge[9]. These subduction zones are associated with only one active volcano that outgasses significant quantities of CO_2 and SO_2 (Barren Island, India[45]), but there are several volcanic centers that have been active during the Quaternary (including Bazman, Taftan, and Koh-i-Sultan in the Makran arc) that are potential sources of diffuse volcanic CO_2 and for which the modern and historical fluxes are unknown[46]. If Khanneshin volcanic CO_2 emissions were comparable to those of the Oldoinyo Lengai carbonatite volcano in Tanzania[47], it could have contributed 2.4 Mt/yr. Currently, most volcanic CO_2 emissions in the region may come from the Tengchong volcanic field, China (4.5–7.1 Mt/yr[48]), which is related to the subduction of the Burma slab[49]. Unless there are major CO_2 sources undetected by satellite measurements[45], the Makran and Andaman-Burma carbon inputs are probably not balanced by volcanic gas emissions, unlike in the Java and Sumatra subduction zones[50]. This suggests that the return of subducted carbon to the atmosphere is inefficient in subduction zones with the highest sedimentary carbon fluxes. In such settings, the carbon inputs must be balanced by carbon mixed into the convecting mantle[5], the storage of carbon in lithospheric reservoirs[6], or both. The Khanneshin volcano is evidence that subducted carbon can rapidly return to lithospheric reservoirs. It may be a rare surface expression of long-lived carbon reservoirs that form via carbonatitic magmatism in rear-arc lithosphere.

Figure captions

Fig. 1: Map of the Makran subduction zone and volcanic arc.

Earthquake focal mechanisms[17] (yellow symbols with approximate depths in km) in the subducting crust indicate that the slab passes beneath the three western volcanic centers[11] (orange). The approximate slab-top depth is contoured by black dashed lines based on earthquake focal mechanism depths. The Khanneshin volcano is slightly north of the linear trend (light grey dashed line) defined by the calc-alkaline volcanic arc centers. After[10].

Fig. 2: $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ systematics of the Makran arc.

The neodymium and strontium isotope compositions of Makran volcanic arc samples testify to sediment recycling. Khanneshin lavas fall along the same Enriched Mantle 2 trend as Bazman and Taftan samples[11,29]; this trend cannot be explained by magmatic fractionation of Rb/Sr and Sm/Nd from mid-ocean ridge basalt values (hatched area) and indicates sediment recycling[35]. The Khanneshin data are from[26] and mantle geochemical trends are after[36]. EM1 = Enriched Mantle 1, EM2 = Enriched Mantle 2, HIMU = high μ, and MORB = mid-ocean ridge basalt.

Fig. 3: Strontium isotopic evidence of rapid sediment recycling.

A, The $^{87}Sr/^{86}Sr$ compositions of Khanneshin carbonatites versus average marine sedimentary carbonates[41]. The horizontal black line and the bounding light grey area represent the mean and 1 standard deviation (n = 20 rocks), respectively, for the Khanneshin carbonatites. Since 500 Ma, average marine sedimentary carbonates equaled that measured in the Khanneshin carbonatites nine times, but only once since 200 Ma. **B**, Same as A, but from 0 to 40 Ma. Sediments deposited in the Indus Fan at c. 30 Ma would have had $^{87}Sr/^{86}Sr$ ratios comparable to those measured in the Khanneshin samples. This implies that sediment recycling through the Makran subduction zone took less than 27 Myr.

Fig. 4: Schematic cross section of the eastern Makran subduction zone. Khanneshin magmas probably derived from subducted sediments that melted near the top of the subducting slab or in buoyant diapirs that ascended into the mantle wedge. Slab depths and the thermal structure are based on earthquake focal mechanisms[17] and thermal modeling[30], respectively. The black dashed line along the top of the subducting Arabian Plate represents the trajectory of subducted Indus Fan material and the time elapsed since entering the trench. Note that only earthquakes with focal mechanisms >50 km deep (white) are plotted in Fig. 1.

Methods (online only)

Strontium isotope measurements

Carbonatite samples were powdered by hand in an agate mortar and pestle. Between 5 mg and 10 mg of each sample was dissolved in a 3:1 mixture of HF and HNO_3. Sr was separated and purified from the samples using Sr-Spec (Eichrom) resin. Sr isotopic measurements were performed on a Thermo-Finnigan Neptune ICP-MS at Woods Hole Oceanographic Institution. Isobaric interferences of ^{87}Rb on ^{87}Sr and ^{86}Kr on ^{86}Sr were corrected for by monitoring ^{82}Kr, ^{83}Kr, and ^{85}Rb and by applying a mass bias correction using an exponential relationship[51]. The internal precision for Sr isotopic measurements was 6–24 ppm. Raw Sr results are normalized using standard SRM987 (^{87}Sr/^{86}Sr = 0.7102140). Standard NBS987 was reproducible to within 25 ppm. See Extended Data Table 1 for strontium isotopic results.

^{40}Ar-^{39}Ar geochronology

At the Oregon State University Argon Geochronology Lab, three phlogopite aliquots were cleaned for 30 min in 200 proof HPLC grade acetone and for 30 minutes in ethyl alcohol, and then were rinsed four times with triple-distilled water and dried at 55 °C for 12 hrs. The samples were irradiated in the Oregon State University TRIGA reactor for six hours, along with Fish Canyon Tuff sanidines[52] that served as flux monitors. Following the procedures described in[53], portions of each phlogopite aliquot (3.882, 9.351, and 4.251 mg for aliquots 1–3, respectively) were loaded in Cu-planchettes and step heated by rastering a 30 W Synrad CO_2 laser beam across each sample under ultrahigh vacuum. Reactive gases were cleaned with AP10 Zr-Al SAES getters at 450 °C and 21 °C before the argon was inlet into an ARGUS VI multicollector mass spectrometer for analysis. Plateau ages (Extended Data Fig. 6)—based on contiguous extraction steps with apparent ^{40}Ar-^{39}Ar dates that are indistinguishable at the 95% confidence interval—were calculated using ArArCALC v.2.6.2 software[54] using the decay constant $5.530 \pm 0.097 \times 10^{-10}$ 1/yr (2σ) from[55] and corrected by[56]. See Data S1, S2, and S3 for the complete results from the Argon Geochronology Lab.

Data Availability

The Ar-Ar geochronology and strontium isotope results are publically available via EarthChem (https://doi.org/10.26022/IEDA/111960).

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Acknowledgments

Robert Seal at the U.S. Geological Survey granted access to the samples, which were collected by U.S. Geological Survey and U.S. Department of Defense Task Force for Business and Stability Operations personnel led by Robert Tucker and Emily King. The Afghanistan Geological Survey provided access to Soviet reports about the Khanneshin volcano that were essential for the fieldwork. The Afghanistan Ministry of Mines and Petroleum granted permission for sample collection. Combined Forces Special Operations Command - Afghanistan provided logistics and security support. At the time of sample collection, F.H. was an employee of TFBSO. Jerzy Blusztajn and Daniel Miggins carried out the strontium isotope analyses and Ar-Ar geochronology, respectively. Comments by Sabin Zahirovic, Elsa Amsellem, and Kwan-Nang Pang, as well as discussions with Sune Nielsen and Glenn Gaetani, improved this paper. This project was supported by the Woods Hole Oceanographic Institution Independent Research & Development Program and a National Science Foundation grant (EAR #1911699) awarded to F.H.

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Contributions

The author participated in the planning, fieldwork, and sample collection at the Khanneshin volcano in 2010. Sample prefixes "FH-" and "KHAN-" correspond to samples collected by the author. F.H. is fully responsible for the conceptualization, methodology, data interpretation, writing, and visualization of this research.

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Ethics declaration

Competing interests

The author declares no competing interests.

Extended Data

Extended Data Fig. 1 Geologic map of the Khanneshin volcano showing sample locations.

The core of the central vent consists mostly of sövite with abundant fenite xenoliths. Outer portions of the central vent are composed mostly of ankerite-barite carbonatite, inferred to be younger than the sövite because they host sövite xenoliths. Samples (white circles) were collected from two drainages that exit the massif to the northeast. This figure is modified from[57] and based on[58] and[23].

Extended Data Figure 2 Mineralogy and petrology of sandstone sample FH-10KH-10.

A, Sawed surface image. The sedimentary clasts are dominantly K-feldspar. Bedding is defined by alternating sandstone and siltstone layers, of which the latter appear darker because they have more interstitial Fe-oxide. The rock is brecciated and crosscut by calcium carbonate veins. **B**, Closer inspection of a carbonate vein reveals anastomosing networks of smaller veins extending into the sandstone. Beneath the large vein is a porous metasomatized region where cavities are partially filled by carbonate minerals, including minor amounts of REE-carbonates. **C**, Thin section photomicrograph. Along calcium carbonate vein margins are secondary Fe-Mn-oxides (black).

Extended Data Fig. 3 Mineralogy and petrology of representative sövite samples. **A**, KHAN-1, hand sample image. Medium- to coarse-grained calcite carbonatite contains fine-grained biotite. Three small fenite xenoliths are visible in the upper left. **B**, KHAN-1, PPL. Small fenite xenoliths, like the one imaged here, are composed of biotite. They share sharp and diffuse boundaries with the surrounding calcite matrix. **C**, KHAN-2, sawed surface image. Larger fenite xenoliths are highly brecciated and crosscut by calcite veins. **D**, KHAN-2, XPL. Large twinned calcite crystal with Fe-oxide and biotite inclusions. Contact twinning separates the upper and lower portions of the crystal, both of which have subtle lamellae twins. **E**, KHAN-2, sawed surface image. Large fenite xenoliths have brecciated textures and are crosscut by multiple generations of veins. The white veins are calcite and the green vein, bound by dashed lines, is mostly apatite. **F**, KHAN-2, XPL. Apatite also forms clusters with biotite in the calcite matrix of sövite samples. **G**, KHAN-2, XPL. Large brecciated fenite xenoliths have biotite-rich zones adjacent to calcite veins and fine-grained interiors composed of biotite and K-feldspar. **H**, RT-10K-09, hand sample image. This sövite contains large (>1 cm) phlogopite books intergrown with coarse calcium carbonate. **I**, RT-10K-09, XPL. Calcite twin lamellae are visible in this sample. Mineral abbreviations: ap = apatite, bio = biotite, cc = calcium carbonate, kfs =

K-feldspar. Hand sample and sawed surface images were taken on a stereomicroscope. Thin section images were taken on a polarizing microscope under plain polarized light (PPL) or cross polarized light (XPL).

Extended Data Fig. 4 Mineralogy and petrology of representative ankerite-barite carbonatite samples.

A, FH-10K-08, sawed surface image. Lath-shaped intergrowths of barium, calcium carbonate, and ankerite form the matrix of this carbonatite. Fe-Mn oxides are present and REE-carbonates line the walls of cavities. **B**, FH-10K-08, PPL. The complex textures of the barium-calcium carbonate intergrowths—perhaps pseudomorphs after witherite—can be observed. Tetraferriphlogopite also exists in this sample as a minor phase. **C**, RT-10K-03, sawed surface image. Ankerite-barite carbonatites also contain fenite xenoliths, as shown here. REE carbonates appear yellow. **D**, RT-10K-03, PPL. Ankerite-barite carbonatites exhibit varied textures. Here, barite (outlined with a dashed line) and ankerite are surrounded by a finer-grained matrix of calcium carbonate. **E**, RT-10K-11, sawed surface image. Intergrowths of ankerite and Fe-oxides often form clusters. **F**, RT-10K-11, PPL. Tabular barite crystals occur in intimate association with ankerite and Fe-oxide. **G**, RT-10K-07, sawed surface image. Some samples are relatively homogeneous on the cm scale. Here, ankerite (grey) surrounds intergrowths of barite (white) and calcium carbonate (also white). Yellow regions contain REE minerals hosted in cavities. **H**, RT-10K-07, PPL. Tetraferriphlogopite is sometime rimmed by REE-carbonate minerals and tends to be associated with barite-calcium carbonate intergrowths. **I**, RT-10K-03, XPL. Solitary fluorite crystals (isotropic) exist in some ankerite-barite carbonatites and are rimmed by calcium carbonate. Mineral abbreviations: ank = ankerite, ba = barite cc = calcium carbonate, fl = fluorite, tfp = tetraferriphlogopite, REE = rare earth element carbonate minerals.

Extended Data Fig. 5 Mineralogy and petrology of REE-rich ankerite barite carbonatites.

A, RT-11K-4A0, sawed surface image. Aggregates of yellow REE-carbonates in a matrix of ankerite, barite, and calcite. Clusters of REE-carbonate and strontianite form lighter yellow clusters. **B**, RT- 11K-4A0, XPL. Contact between REE-carbonate aggregates and ankerite-barite-calcite matrix. **C**, RT-11K-5B3B, sawed surface image. Ankerite (dark brown patches) plus calcite (grey) zones alternate with barite, strontianite, and REE-carbonate aggregates. **D**, RT-11K-5B3B, XPL. Spherulitic acicular strontianite occurs in association with ankerite, calcium carbonate, and barite. **E**, RT-11K-2B, XPL. In some cases, subhedral domains of barite and ankerite are rimmed by zones of ankerite, strontianite plus REE-carbonates, and apatite. **F**, RT-11K-5B6C, XPL. Mn oxides occur as veins and clusters. Here, tabular Mn-oxide in a vein contains interstitial calcium carbonate, which grades into intergrowths of strontianite and REE-carbonate minerals. Mineral abbreviations: ank = ankerite, ba = barite, cc = calcium carbonate, REE = rare earth element carbonate minerals, str = strontianite.

Extended Data Fig. 6 ^{40}Ar/^{39}Ar plateau diagrams.

A-C, Step heating analyses of RT-10K-09 phlogopite aliquots 1–3, respectively.

Extended Data Fig. 7 Trace element model.

A, The trace element concentrations in the Khanneshin carbonatite samples vary by roughly 1–2 orders of magnitude for each element (grey shaded region). In general, sövite samples are less enriched than ankerite-barite carbonatites. Colored lines represent mean compositions for Khanneshin sövites and ankerite-barite carbonatites with (“REE”) and without (“A-B C”) abundant REE minerals. **B**, The modeled composition of carbonatitic melt derived from subducted Makran sedimentary material—assumed to equal average Indus Fan sediments[59]—and Khanneshin carbonatite samples (grey shaded region) have similar trace element patterns. The model assumes that 30% melting of subducted sediments produced a carbonated silicate magma that separated into immiscible carbonatitic and silicate magmas during ascent. See Supplementary Information text for details. All values are normalized to primitive mantle[60].

Extended Data Table 1 Strontium isotope results.

^{87}Sr/^{86}Sr results for 20 Khanneshin carbonatite samples and one sandstone.

Extended Data Table 2 Trace element abundances.

Trace element abundances (μg/g) in the Khanneshin samples[23,27].

Supplementary Information

Supplementary Information Text

Sample descriptions and trace element model.

Data S1

The complete $^{40}Ar/^{39}Ar$ geochronology report received from Oregon State University Argon Geochronology Lab for RT-10K-09 phlogopite aliquot 1.

Data S2

The complete $^{40}Ar/^{39}Ar$ geochronology report received from Oregon State University Argon Geochronology Lab for RT-10K-09 phlogopite aliquot 2.

Data S3

The complete $^{40}Ar/^{39}Ar$ geochronology report received from Oregon State University Argon Geochronology Lab for RT-10K-09 phlogopite aliquot 3.