Stratigraphic evidence for an early collision between northwest India and Asia

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THE collision of India with Asia[1] had a profound influence on late Cretaceous and Cenozoic oceanography[2], climate[3], faunal extinctions[4] and the motion of at least some of the Earth's lithospheric plates[5]. As the collision ended a period of rapid Indo-Asian convergence[6], a precise knowledge of its timing (when the crust of the neo-Tethys ocean was completely subducted[7], at some point along the plate boundary) is important for understanding its wider consequences. But current estimates of the collision age range from 65 to 38 Myr before present[6,8–11]. Here we report the results of extensive biostratigraphic analyses from Waziristan and Kurram in northwest Pakistan, which show that accretionary-prism and trench strata were first thrust onto the northwest Indian passive margin after 66 Myr but before 55.5 Myr. After this time, volcanic-arc fragments, the accretionary prism, trench material and imbricates of the north Indian slope were raised to shallow water depths and overlapped by upper Palaeocene shallow-water carbonates and shales[12–14], indicative of post-collision thrusting in this region. Finally, both the suture and the Indian craton were overlapped by continuous unconformable upper Lower Eocene shallow-marine strata, demonstrating that suturing was complete by 49 Myr.

Before the collision of the northwest Indian craton with Asia, an accretionary prism and an associated composite of previously accreted volcanic arcs and microplates formed the southern margin of Asia above the northward-subducting crust of the neo-Tethys ocean[7,9]. Due to inevitable irregularities in the pre-collisional margins of India and Asia, possible collisional obliquity and variable rotation of India with respect to Asia during the Cenozoic era, it is likely that collision was not synchronous across the entire collision zone[6,7]. Nevertheless, the most commonly cited age for early Indo-Asian collision (~50 Myr) comes from Ladakh in the western Himalaya[7 9,15].

But interpretation of the Ladakh data is ambiguous for the following reasons: (1) two discrete tectonic events, ophiolite obduction (75–60 Myr) and collision (55–36 Myr), separated by unconformable Palaeocene strata have previously been postulated[8,9,15]; (2) the actual cause of flexural unconformities[16] is unknown, because flexure of this magnitude could result from intraplate stresses[17] or ophiolite obduction[7,18] rather than collision itself; (3) Lower and Middle Eocene volcaniclastics of the Indian shelf[16,19] are not structurally linked to a specific allochthon; (4) the age of unconformable terrestrial strata which overlap both India and Asia in Ladakh is not known with precision (±13 Myr)[7]; (5) the age of the last marine sediments in the suture zone does not necessarily represent a maximum age for collision[7,15] as demonstrated here.

We report the results of recent stratigraphic, structural and chronological studies in the Kurram and Waziristan tribal areas

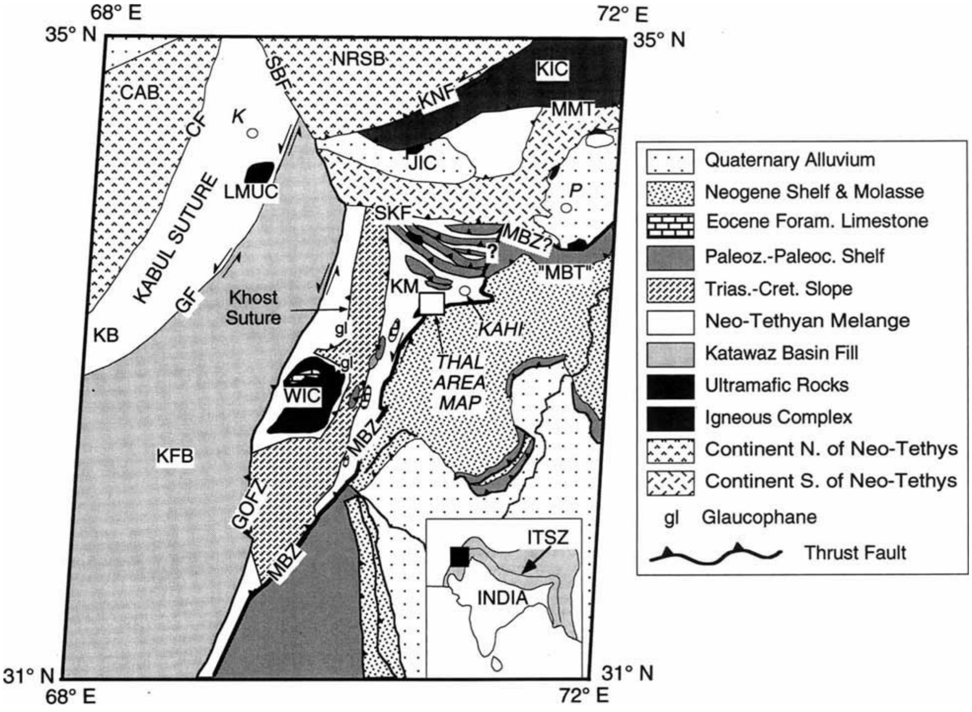

FIG. 1 Main figure, geological map of northwest Pakistan and eastern Afghanistan[27,58]. Locations: K, Kabul; P, Peshawar. Tectonic boundaries: CF, Chaman fault; GF, Gardez fault; GOFZ, Gwarar Oba fault zone; KNF, Kunar fault; MBT, main boundary thrust; MBZ, mélange boundary zone; MMT, main mantle thrust; SBF, Sarubi fault; SKF, Safed Koh fault. Lithosomes: CAB, central Afghan block; JIC, Jalalabad igneous complex; KIC, Kohistan igneous complex; KB, Kabul block; KFB, Katawaz Flysch basin (Khojak Flysch); KM, Kahi mélange; LMUC, Logar mafic-ultramafic complex; NRSB, Nooristan block; WIC, Waziristan igneous complex. Interpretation of the Waziristan igneous complex as part of a volcanic arc[26] is bolstered by a suite of intrusive and extrusive rocks that resemble the igneous complexes of the Kohistan arc[59,60], including ultramafic rocks with high-pressure amphibole and pyroxene mineral chemistries[26]. The WIC includes dacite, rhyodacite, andesite, tuff, agglomerate, volcanic breccia and copper deposits[14,26,61] typical of arc volcanism[61]. Thick sections of pyroclastic breccia with decimetre-sized bombs and layers of tuff up to 3 m thick in the upper part of the WIC[14] preclude a mid-oceanic-ridge origin[61]. Interbedded Albian carbonate with *Flabellamina* sp., radiolarite and siliciclastic sediments containing algae, gastropods, and lamelibranchs indicate that explosive volcanism occurred after the end of the Early Cretaceous (⩽94 Myr). Inset, map of India and surrounding area showing location of main figure and Indus-Tsangpo suture zone (ITSZ).

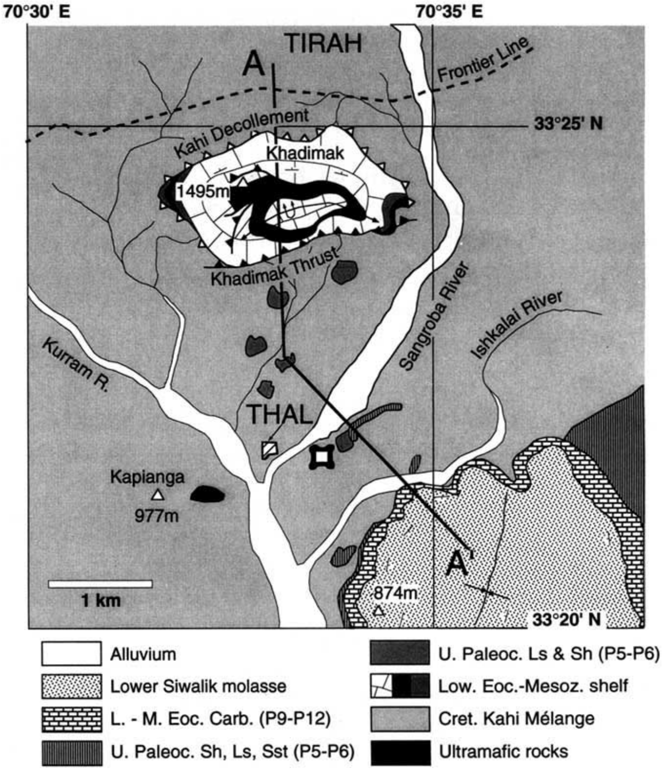

FIG. 2 Geological sketch map of the Thal area[12]. The Kahi mélange contains the Kapianga mafic-ultramafic complex. Together they are composed of dunite, peridotite, pillow basalt[26,62], glaucophane-bearing[14,62] tuff which locally encases Cenomanian *Rotalipora cushmani*, manganese nodules, kilometre-scale blocks of Upper Cretaceous radiolarite[22] including *Cryptamphorella conara* and *Amphipyndax pseudoconulus*, Mesozoic belemnite-bearing calcilutite, and Turonian (*Helvetoglobotruncana helvetica*, *Praeglobotruncana stephani*, *Whiteinella brittonensis*, *Marginotruncana* sp.) to Maastrichtian (*Heterohelix navarroensis*, *Globotruncana arca*, *Globotruncana bulloides*) deep-marine shale which contains centimetre-to-metre sized olistoliths including coral fragments, turbidites containing volcaniclastic sandstone with Campanian–Maastrichtian open marine foraminifera (*Globotruncana gansseri*, ?*Abathomphalus mayaroensis*) and non-volcaniclastic sandstone[20]. The Kahi mélange is a previously unrecognized segment of the neo-Tethyan accretionary prism/trench complex which crops out over >15,000 km^2 of the tribal areas of northwest Pakistan and eastern Afghanistan[20] (Figs 1 and 2). This rock assemblage represents a link between segments of the neo-Tethyan suture on the northern and western margins of the Indian craton[63,64] (Fig. 1), and serves to explain the abundance of published occurrences of ultramafic rocks between Waziristan-Kurram and well accepted Indus suture outcrops north and west of the Peshawar basin in northern Pakistan[21,60,65–67] (Fig. 1). The youngest strata preserved in the accretionary prism/trench complex date from late to latest Maastrichtian and provide a maximum age constraint for the beginning of collision in this area (Fig. 2). Lithologies: Sh, shale; ls, limestone; Sst, sandstone; Carb, carbonates in general.

of northwest Pakistan, where distinct episodes of collision and post-collisional thrusting can be discerned in the Palaeocene-to-Eocene stratigraphic record. During the first episode, continental collision, the accretionary prism and trench complex were thrust on to the north-facing continental rise and slope of the Indian craton and raised to shallow water depths before being overlapped by shallow marine Upper Palaeocene strata. During the second episode, volcanic-arc fragments, the accretionary prism, trench complex and imbricates of the north Indian slope and shelf were thrust further across the Indian shelf, largely eroded, and subsequently overlapped by upper Lower Eocene limestones which are continuous with the Indian shelf sequence. These overlapping and cross-cutting relationships provide the oldest unambiguous constraints on the timing of collision and suturing in this region as well as the entire Himalaya.

Our field work[20] and re-interpretation of published data[12,21,22] indicates that remnants of the Indo-Asian suture are present 100–300 km southeast of its previously recognized trace[23–25] (Fig. 1). Three major lithologic elements define the suture in Waziristan and Kurram (Fig. 1): (1) the large ultramafic-to-acidic Waziristan igneous complex (WIC)[26] which represents a segment of the trans-himalayan arc[20] (Fig. 1); (2) the intensely

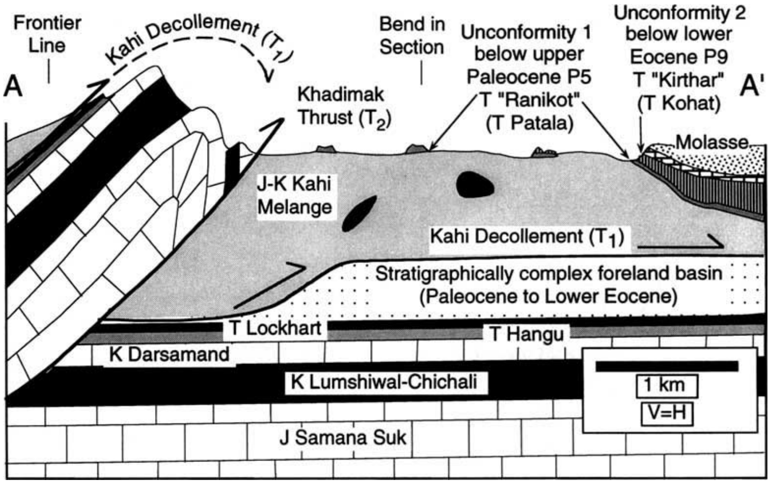

FIG. 3 Simplified geological cross-section of the Thal area[12,22] along A–A′ in Fig. 2. Unconformity 1 occurs where Upper Palaeocene shelf limestones and shales depositionally overlap the Kahi mélange[12]. Although this contact has been interpreted as a southeast-vergent thrust fault[22], our mapping results and those of Davies[12,21] indicate that it is primarily a depositional contact. The Late Palaeocene age is supported by four species of Palaeocene molluscs[12], four species of Palaeocene corals[12], and new foraminiferal biostratigraphic studies near Kahi which indicate that these strata encompass faunal zones P5 and P6. Unconformity 1 defines initial collision between the Waziris-tan-Kurram segment of the trans-Himalayan arc and the Indian craton in this region. Initial thrusting of the accretionary prism on to the Indian slope occurred between 66 and 55.5 Myr. This scenario is corroborated by the development of an adjacent marine to non-marine foreland basin on the northwest Indian craton[68] as well as significant pre-Eocene deformation of the shelf sequence in northern Pakistan[69]. Unconformity 2 developed when the arc/prism/trench complex and Indian slope were thrust farther on to the Indian shelf. Detritus included a massive influx of Jurassic dinoflagellates and pollen which was redeposited in the adjacent foreland basin. That basin progressed from shale-dominated, marine deposition to subaerial red beds analogous to the Balakot–Murree formation found in the Jhelum re-entrant of northern Pakistan[70]. The eroded arc/prism/trench complex and the gently folded, unconformable Upper Palaeocene strata were subsequently overlapped above a clear unconformity by shallow-marine strata of the P9 foraminiferal zone (50–49 Myr), substantially after collision. V = H, vertical = horizontal. Geological periods, J, Jurassic; K, Cretaceous; T, Tertiary. The names that follow these abbreviations refer to layers or masses of rock.

deformed ultramafic- and glaucophane-bearing Kahi mélange, which represents the neo-tethyan accretionary prism and trench complex (Figs 1 and 2); and (3) non-volcaniclastic, deep-to-shallow marine carbonates, shales and sandstones of the northwest Indian shelf and slope[14,27,28].

The WIC and Kahi mélange must be placed in the context of Afghan tectonics to address the issue of Indo-Asian collision because two sutures separate the northwest Indian craton and central Afghanistan (Fig. 1)[27]. The central Afghan block (CAB) has been a part of Asia since at least the early Cretaceous period[27]. The northwestern suture (the Kabul suture), closed during the Palaeocene[27] when the Gondwanan Kabul block was accreted to the southeastern margin of the CAB extinguishing the northern Kandahar arc (111-69 Myr)[29]. Unconformable Early Eocene strata overlie the Kandahar arc, imbricates of ultramafic rock, metamorphosed Gondwanan shelf and slope of the Kabul block, and remnants of a Late Cretaceous accretionary prism/trench complex[14,28,30-41].

Igneous rocks of the WIC were thrust onto the northwest Indian craton during the Palaeocene[14,27]. Re-interpretation of the WIC as a volcanic arc or arc fragment[26], and of strata along the southeastern boundary of Waziristan and Kurram as imbricates of Indian slope and accretionary prism/trench complex[20], implies that overlying unconformable Upper Palaeocene (P5) and Upper Eocene (P9) strata[12,13,42 46] date collision and full suturing rather than an intra-oceanic ophiolite obduction event followed by collision. Moreover, the similar Palaeozoic to Eocene tectonostratigraphies of the Kabul (northwest) and Khost-Waziristan (southeast) Sutures[27] suggest they are the same suture, now repeated in cross-section and map view (Fig. 1). Therefore our revision of the geology of Waziristan and Kurram supports the hypothesis that the Kabul block (Fig. 1) represents a corner of the northwest Indian craton which was broken off and extruded[47] towards the southwest[48] after the collision of northwest India and Asia.

The newly recognized mélange boundary zone (MBZ) separates the Kahi mélange from regions of exclusively Indian shelfal strata. In the northern and southern parts of the study area (Fig. 1), the MBZ is generally a southeast-vergent thrust above the Permo-Triassic to Cretaceous shelf sequence. In its central part, however, the MBZ is usually represented by one or more Tertiary unconformities. The two oldest unconformities are defined by the overlap of parts of the Kahi mélange by parautochthonous strata of the Indian shelf[12,21,22] (Figs 2 and 3). Despite local structural disruption due to exploitation of some of the unconformities by back thrusts, the fundamental stratigraphic relationships of the unconformities are locally preserved near the town of Thal (Figs 1 and 2). The unconformable Palaeocene strata which overlie the prism/trench/slope complex indicate they were juxtaposed before the end of the P5 foraminiferal zone (>55.5 Myr)[12,13,21,42-46,49-53] (Figs 2 and 3).

During continued thrusting, the Kahi mélange overran Lower Palaeocene shelf limestones and parts of its own foreland basin (Fig. 3). This thrust contact is exposed on the west, north and east sides of Khadimak mountain (Fig. 2), where a regional décollement places the Kahi mélange above Late Palaeocene to Early Eocene (P6) Indian shelf strata (Fig. 3). North of Thal, numerous thrust imbricates of shelf strata cut upward through the basal décollement of the Kahi mélange in a style analogous to that found at Khadimak mountain (Fig. 2)[22]. Although we can not precisely quantify the amount of shortening represented by transpressional deformation north of the MBZ[54], the present locations of these imbricates with respect to the MBZ suggest a lower limit of 180 km for the amount of shortening during thrusting of the Kahi mélange on to the northwest Indian craton.

Upper Lower Eocene (P9) strata at Thal fort (Fig. 2) can be traced from their unconformable contact with the supra-mélange Palaeocene strata along strike to a continuous stratal succession above the north Indian craton[22,55]. This is the first continuous pre-Middle Eocene physical link between a neo-Tethyan accretionary prism/trench complex and the Indian craton ever reported. Because the Kabul suture (whatever its relationship to the Khost-Waziristan suture) had already closed during the Palaeocene[14,27], the upper Lower Eocene shallow-marine strata at Thal and elsewhere in Waziristan[12,13,21,42-46,49-53] also date full suturing of the northwest Indian craton with Asia. The similarity of the timing of full suturing of the WIC/Kahi mélange and of oceanic igneous complexes farther south along the western Indian plate margin[56] suggests simultaneous modification (>49 Myr) of the northern convergent and western transform plate boundaries. This is consistent with the idea of post-collisional transpressional transitions from convergent to transform plate margins[54,57]. Because the suture has been "stitched" to the Indian craton since 49 Myr, and because <100 km of shortening has occurred south of the suture since then[54], nearly all Indo-Asian convergence that occurred after 49 Myr (⩾2,000 km)[6] has been accommodated north of the suture in this area. ☐

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An experimental replication of upper-mantle metasomatism

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INTERACTION of melts ascending from the asthenosphere with the lithospheric mantle through which they pass is widely accepted to be a significant process by which the lithosphere can acquire distinctive trace-element and isotopic signatures[1–3]. Despite the importance of this process in the genesis of the lithosphere, the nature of these 'metasomatic' reactions is still debated[2–5]. Here I report the results of an experiment designed to investigate the mechanism by which such metasomatism could occur. A natural sample of Group I kimberlite, a low-volume partial melt of asthenospheric origin, is reacted with a refractory peridotite (harzburgite) in a thermal gradient at high pressure to simulate the interaction between a dyke and its host rock in the lower lithosphere. The harzburgite develops several contrasting mineralogical zones, the coolest of which contains olivine, orthopyroxene, clinopyroxene, phlogopite, amphibole, Nb–Cr-rutile and minor zircon. The formation of mica and amphibole is accompanied by increases in trace-element concentrations and Rb/Sr, Rb/Ba and Pb/U ratios—features characteristic of metasomatized xenoliths recovered from southern African kimberlites[5]. These results support the suggestion, based on temporal association and isotopic data, that at least some mantle metasomatism is related to the interaction of Group I kimberlite with refractory peridotite in the lower lithosphere[6].

The mantle xenoliths that occur in kimberlites have received much attention (for example, refs 7–10) because they provide the best direct evidence of the nature of the lithospheric mantle. Among the xenolith types that occur in the Group I kimberlites of southern Africa (see Fig. 1 legend for definition of Group I kimberlite), some show evidence of chemical alteration (metasomatism) in the mantle[11,12]. In addition to the usual olivine, pyroxenes and garnets typical of many peridotites, these 'metasomites' contain distinctive phlogopite ± alkali-rich amphibole and, in some cases, Nb–Cr-rutile and Ba-titanates. Trace-element studies have shown that the metasomatism has resulted in the development of high Rb/Sr, Rb/Ba and K/Ba, and an enrichment in light rare-earth elements. The metasomites also have high $^{87}Sr/^{86}Sr$ (ε_{Sr} from +18 to +80; ε notation defined in Fig. 2 legend) at $^{143}Nd/^{144}Nd$ only slightly lower than that of the bulk Earth (ε_{Nd} from 0 to −7)[1]. Metasomatism is thus an important process by which the lower lithosphere becomes enriched in both trace and major elements. The nature of the metasomatic 'fluid' (which could be an aqueous fluid or a melt) remains debated, however, because there is no clear relationship between the metasomite trace-element characteristics and any magma type of deep origin[1,13]. This has led to the suggestion that metasomatic assemblages are the results of complex open-system reactions in which material is both added from, and removed by, melts and fluids passing through peridotite[1].

To test whether the metasomite xenolith assemblages are the products of interaction between a low-volume melt and refractory lithosphere, I have devised an experiment in which natural, aphanitic Group I kimberlite can interact with refractory peridotite in conditions that simulate reaction between a dyke and its wall-rock. A 10-mm-long capsule is loaded with a 'sandwich' consisting of a layer of natural aphanitic kimberlite (S30; ref. 14) overlying a layer of synthetic refractory peridotite (LBM10; ref. 15) in the proportions 1:9 by weight. This capsule is enclosed in an outer capsule containing magnesite + periclase + graphite + H_2O to buffer the oxygen fugacity of the experiment close to the enstatite + magnesite + olivine + graphite (EMOG) equilibrium[16]. The capsule assembly is then placed in a standard piston–cylinder high-pressure apparatus in such a way that at run conditions (30 kbar, 24 h) the kimberlite occupies the furnace hot-spot (1,225 °C), whereas the refractory peridotite extends downwards into the thermal gradient to reach a temperature of 1,000 °C at the base of the capsule. The conditions at the capsule base thus simulate those found at ~90 km depth in a geotherm of 40 mW m^{-2}. After quenching, the capsule released 2 wt% of a water-rich fluid, indicating vapour-saturation at run conditions.

The run products consist of six transverse layers of contrasting colour and texture. The highest-temperature layer consists of a small volume (~0.5 mm thick) of radiating, bladed crystals interpreted to be the quench products of residual kimberlite melt. Below are a series of peridotite types of decreasing grain size. The two higher-temperature peridotite layers consist of 2 mm of Cr-spinel + olivine (Cr-sp + ol) overlying 2 mm of Cr-sp + ol + clinopyroxene (cpx), both assemblages containing interstitial glass and phlogopite (phl) crystals. Below these assemblages is a sequence of porous peridotites containing no material identifiable as quench products after a melt phase. This sequence runs

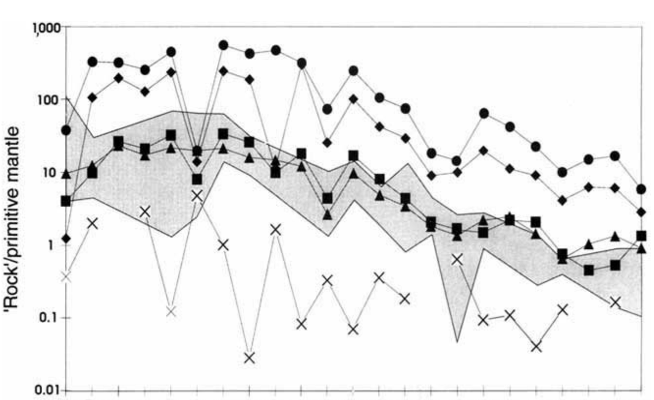

FIG. 1 Bulk trace-element patterns determined by secondary-ion mass spectrometry of fused samples using the method described in ref. 24. Starting materials: circles, aphanitic kimberlite S30; crosses, synthetic harzburgite LBM10. Run products: diamonds, residual kimberlite melt; squares, phlogopite lherzolite; triangles, phlogopite, K-richterite lherzolite. Shaded area: maximum and minimum of range shown by phlogopite, K-richterite peridotite xenoliths[4]. Kimberlites are volcanic rocks that are SiO_2-poor and relatively rich in MgO and K_2O: Group I kimberlites are poorly micaceous and have relatively low abundances of SiO_2, MgO and K_2O compared with the mica-rich Group II kimberlites.