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Geochemical evidence for the melting of subducting oceanic lithosphere at plate edges

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Most island-arc magmatism appears to result from the lowering of the melting point of peridotite within the wedge of mantle above subducting slabs owing to the introduction of fluids from the dehydration of subducting oceanic crust[1]. Volcanic rocks interpreted to contain a component of melt (not just a fluid) from the subducting slab itself are uncommon, but possible examples have been recognized in the Aleutian islands, Baja California, Patagonia and elsewhere[2–4]. The geochemically distinctive rocks from these areas, termed 'adakites', are often associated with subducting plates that are young and warm, and therefore thought to be more prone to melting[5]. But the subducting lithosphere in some adakite locations (such as the Aleutian islands) appears to be too old and hence too cold to melt[6,7]. This implies either that our interpretation of adakite geochemistry is incorrect, or that our understanding of the tectonic context of adakites is incomplete. Here we present geochemical data from the Kamchatka peninsula and the Aleutian islands that reaffirms the slab-melt interpretation of adakites[2], but in the tectonic context of the exposure to mantle flow around the edge of a torn subducting plate. We conclude that adakites are likely to form whenever the edge of a subducting plate is warmed or ablated by mantle flow. The use of adakites as tracers for such plate geometry may improve our understanding of magma genesis and thermal structure in a variety of subduction-zone environments.

In the northwesternmost Pacific, there is a dramatic shift in subduction dynamics where the Aleutian and Kamchatka arcs meet at an angle of nearly 90° (Fig. 1). Well defined, deep seismic zones indicate that the subducting Pacific plate dips to the west beneath Kamchatka, and to the north beneath the central Aleutians, but the nature of subduction beneath the junction of these arcs is not well understood. One recent study suggests that the subducting Pacific plate is not present beneath the western Aleutians, and therefore does not bend sharply beneath the corner formed by the Aleutian–Kamchatka junction[8]. This interpretation, which is a significant departure from some previous views[9], implies that the western Aleutians are a simple transform boundary, and that there is a window through the subducting Pacific plate beneath the western Aleutians and the Aleutian–Kamchatka junction. In turn, this implies that as the Pacific plate passes beneath the Aleutian–Kamchatka junction, it is exposed to shearing and mantle flow around its northern edge—a situation that is likely to cause this edge to be anomalously hot and/or physically ablated[8]. Northward shoaling of seismicity beneath Kamchatka supports this view of slab geometry (Fig. 2). The implications for magma genesis in the Aleutian–Kamchatka junction are clear: if the edge of the slab is heated sufficiently, it may contribute a melt (not just a fluid) to the source of magmas erupted in the vicinity of Sheveluch volcano, the northernmost active strato-volcano in Kamchatka (Fig. 1).

The effects of slab melting on arc magma geochemistry are incompletely understood, but many workers believe that a distinctive class of magnesian and calc-alkaline andesites and dacites termed 'adakites'[5] (see Fig. 3 regarding our use of this term) may be examples of arc volcanic rocks that are produced in part by melting of subducting oceanic crust. Studies of adakites indicate that the geochemical consequences of slab melting may be anomalously steep rare-earth-element patterns, high Sr contents and high Sr/Y ratios in andesitic-to-dacitic rocks that may also be relatively rich in compatible elements such as Mg, Cr and Ni. These features, which are most commonly seen in arcs where the subducting oceanic lithosphere is relatively young[5], are thought to be produced when subducting oceanic crust melts at high pressures to produce silicic magmas that rise through—and react with—the overlying wedge of mantle peridotite[2].

Figure 3 shows that volcanic rocks of the Sheveluch area are significantly more Mg-rich (lower FeO*/MgO) at a given SiO_2 content than are rocks from the adjacent volcanoes of the Klyuchevskoy group. (FeO* is total iron content calculated as FeO.) Figure 4 shows that with regard to Sr/Y, the Sheveluch rocks fall

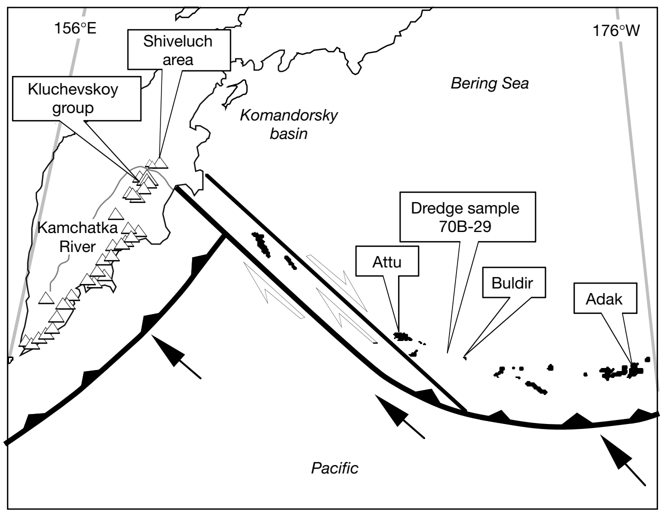

Figure 1 Map view of the study area. The figure shows the oblique subduction zone of the central Aleutians (near Adak), the transform-type boundary in the westernmost Aleutians, and the sharp bend into the subduction system of the Kurile–Kamchatka arc. The Klyuchevskoy volcanic group and the Sheveluch area mark the location of the Kamchatka central depression. Exceptionally voluminous arc volcanism in the central depression, and the slight offset of the magmatic front in this area (apparently due to a slight flattening of the slab dip[27]) are believed to be evidence of mantle flow around the northern edge of the subducting Pacific plate as it passes beneath the Aleutian–Kamchatka junction[8].

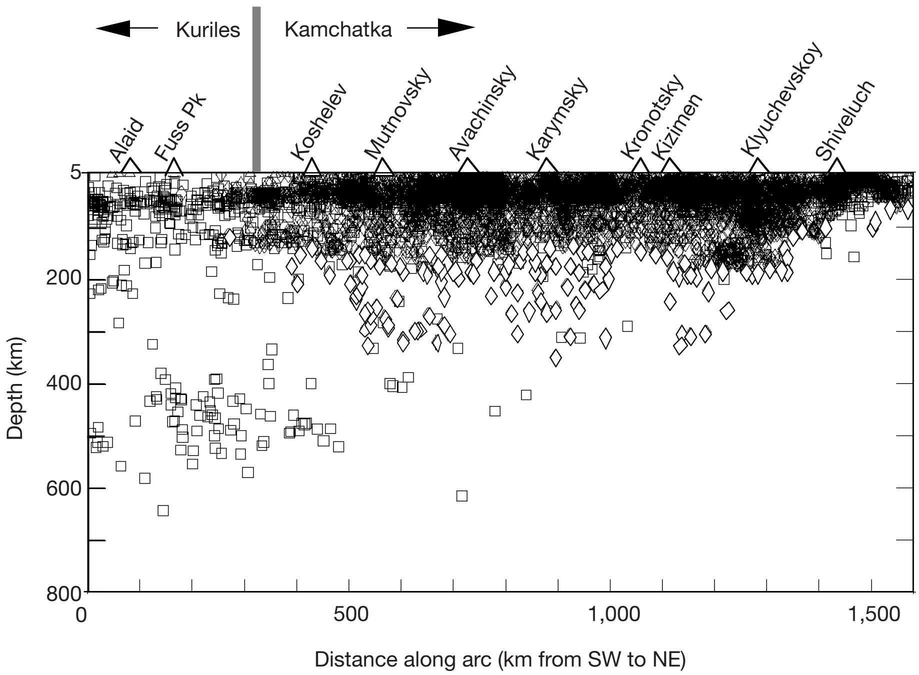

Figure 2 Along-arc seismicity in the Kurile–Kamchatka system. The figure illustrates the northward shoaling of seismicity towards the Aleutian–Kamchatka junction. The absence of deep earthquakes beneath the Aleutian–Kamchatka junction is interpreted to imply that mantle flow around the northern edge of the Pacific plate (possibly induced by slab roll-back) has significantly warmed and physically ablated the subducting plate beneath this junction[8]. Distinctive geochemical features of volcanic rocks from the Sheveluch area (Figs 3, 4) are interpreted to be the result of anomalous heating of the plate along its northern edge beneath the Aleutian–Kamchatka junction. Earthquake locations are from refs 27 (diamonds) and 28 (squares). White triangles mark the locations of the major volcanic centres along the arc.

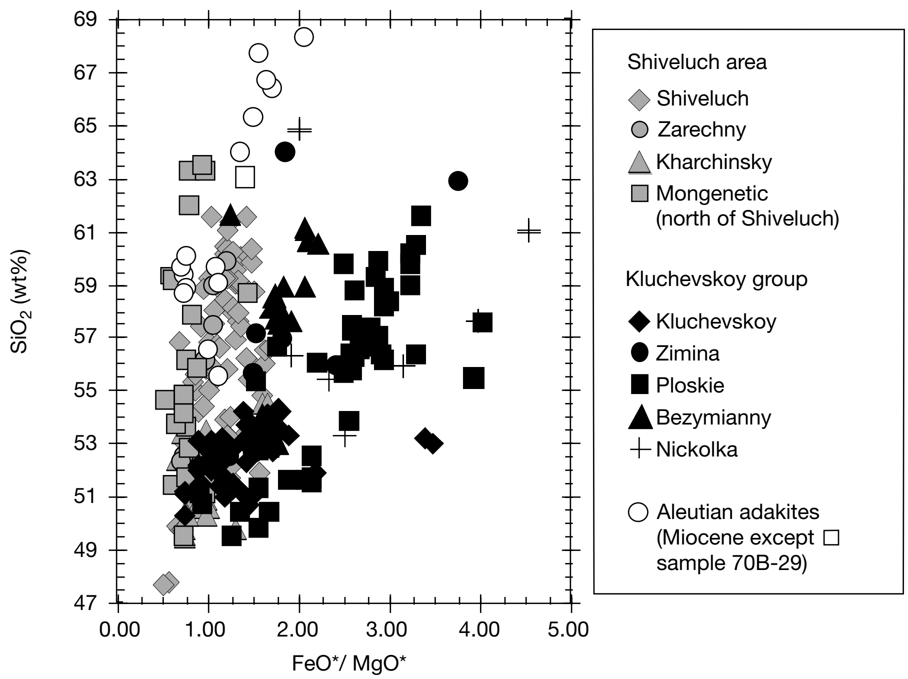

Figure 3 Whole-rock SiO_2 content versus FeO*/MgO ratio in volcanic rocks of the Kamchatka central depression compared to Aleutian adakites. Kamchatka data are grouped geographically from areas immediately north (Sheveluch area) and south (Klyuchevskoy group) of the Kamchatka River (see also Fig. 1). We use the term 'adakite' throughout this Letter to describe calc-alkaline andesites and dacites that are relatively Mg-rich (low FeO*/MgO, high Mg/(Mg+Fe)) and also have anomalously high Sr/Y (>50) compared to 'normal' arc volcanic rocks (Sr/Y not shown here, see Fig. 4). This graph shows that rocks from the Sheveluch area are more Mg-rich relative to SiO_2 than are those from the adjacent Klyuchevskoy group. We attribute the contrasting trends, in part, to the presence of primitive andesites containing an adakitic geochemical component in the rocks of the Sheveluch area. The primitive andesites have high SiO_2 relative to FeO*/MgO, and this difference is interpreted to persist throughout the fractionation and mixing processes by which these magmas evolve[24]. This graph includes 142 data points from the Sheveluch area and 147 from the Klyuchevskoy group. Published data ($n = 74$) are from refs 29–32.

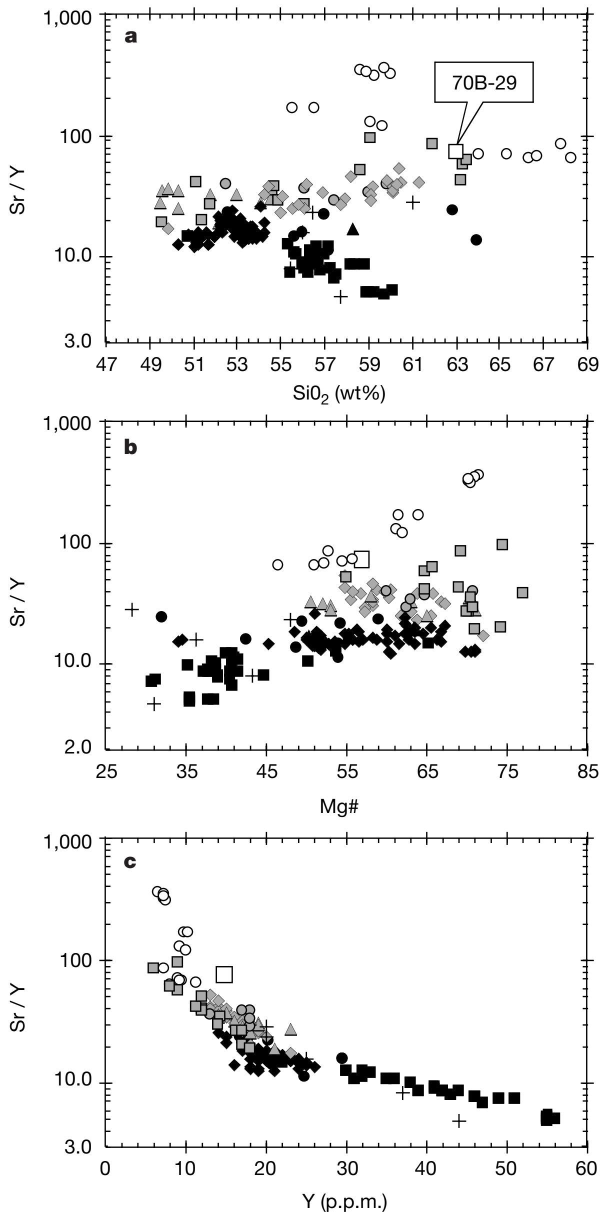

Figure 4 Sr/Y ratio versus SiO_2 content, Mg# and Y content for volcanic rocks of the Kamchatka central depression compared to Aleutian adakites. Symbols are the same as in Fig. 3; Mg#= 100[Mg/(Mg + Fe)] calculated on a molar basis using total Fe content. We emphasize Sr/Y because this parameter is interpreted to be a strong indicator of slab melting, and because these trace elements are relatively well represented in the available data. The Sheveluch and Klyuchevskoy data fields overlap in the range of Sr/Y = 10–25, which are common values for primitive arc volcanic rocks. The distinctive aspect of the data set from the Sheveluch group is the common occurrence of low Y (<17 p.p.m.) with high Sr/Y (>30), especially in samples with relatively high Mg# and high SiO_2. A crystal fractionation or AFC (assimilation-fractional crystallization) origin for this trend is unlikely, though the effects of fractionation are clear in the Klyuchevskoy data which show strong trends toward decreasing Sr/Y with increasing SiO_2 (**a**), decreasing Mg# (**b**), and increasing Y (**c**). For some samples plotted here, including most of the adakites and all of the samples from Ziminy volcano, available Yb data have been used to estimate the concentration of Y by assuming that Y/Yb = 10.5. Variation of the assumed Y/Yb value within reasonable limits (9–12) has no significant affect on the appearance of these graphs. The distinctive characters of the samples from Sheveluch area and the Klyuchevskoy group are clearly resolved, even though data were acquired by several laboratories over many years. The number of data points plotted here differs from Fig. 3 because Sr and Y are available for only a subset of samples. Published data sources here are the same as in Fig. 3.

between Aleutian adakites and 'normal' arc volcanic rocks of the Klyuchevskoy group. These data show that the rocks of the Sheveluch area are chemically distinctive in ways that are consistent with the possible presence of a slab-melt component in their source. The strong adakite geochemical signature in samples from the monogenetic centres probably reflects the fact that these rocks did not pass through the magmatic plumbing system beneath Sheveluch proper, and therefore underwent comparatively little fractionation and mixing with 'normal' arc magmas—processes that will generally dilute the adakite geochemical component from the slab[10].

Combining geophysical, geochemical and dynamical observations, we find significant support for the idea of a slab window and subducting plate edge beneath the Aleutian–Kamchatka junction[8]. This view implies that there exists an active tear in the subducting Pacific plate somewhere beneath the western Aleutians (Fig. 5). The location of the tear is not constrained by seismicity, but the geochemistry of active western Aleutian magmatism suggests that it may be located between Buldir and Attu islands, where the arc switches from convergent to strike-slip motion. Sampling of volcanic rocks in this area is sparse, but in this context a singular rock, sample 70B-29, is of interest. Sample 70B-29 is a hornblende-bearing andesite with geochemistry that places it outside the norm for Aleutian volcanic rocks, but squarely among the adakites (Figs 3, 4). Sample 70B-29 is by far the youngest Aleutian adakite available (<610,000 years old[11]), and it is the only one that can be placed with confidence in the modern tectonic context. This sample was dredged from the sea floor approximately 80 km west of Buldir island[11], where the subducting plate is approximately 50 Myr old[12]. According to thermal models, this subducting lithosphere is too old and cold to melt beneath the arc[6,7], so the association of adakitic volcanism with young subducting lithosphere cannot apply in this case. We argue that adakite sample 70B-29 was produced by melting along the edge of the Pacific plate at the point where it is being torn in an unzipping motion as it passes beneath the western Aleutians (Fig. 5). We infer from this case that Miocene adakites in the Aleutians probably also resulted from melting along the edge of a torn Pacific plate, possibly as the locus of the tear migrated along the arc during Neogene times.

In general, it seems that melting at plate edges is possible in all cases of ridge subduction and slab window formation (for example, Baja, Patagonia). A slab window similar that of the Aleutian–Kamchatka junction exists in northern California, where the Mendocino triple junction bounds the Cascade subduction system to the north, and the San Andreas transform to the south. In the Cascades, adakitic andesites occur only at Mts Shasta and Lassen[13,14], which lie close to the triple junction, above the southern edges of the subducting Juan de Fuca and Gorda plates. Here, the adakite geochemical component seems to be spatially linked to plate edges near the triple junction, but apparently not to the subduction of young lithosphere beneath Oregon and southern Washington[15,16]. The occurrence of geochemically distinctive primitive andesites in the Pliocene-age Clear Lake Volcanics (high Mg content and La/Yb ratio, low $^{87}Sr/^{86}Sr$ ratio)[17,18] suggests that adakite geochemistry may also be a common feature of magmatism associated with the northward migration of the Mendocino triple junction in the Neogene. In Costa Rica, adakite genesis has been linked to the melting of young and hot lithosphere during subduction of an extinct segment of the Galapagos spreading centre[19], but if adakites can also form by melting along the edges of plates that are older, then the possible role of alternative subduction geometries must be considered[20]. The unusual case of adakite genesis at Solander island, located south of New Zealand's South Island[21] may also be associated with a subducting plate edge. The tectonic geometry in this place is poorly understood[21], but geophysical observations are consistent with the bending, and possible tearing, of the Australian plate as it passes beneath the Pacific plate at a highly oblique angle[22].

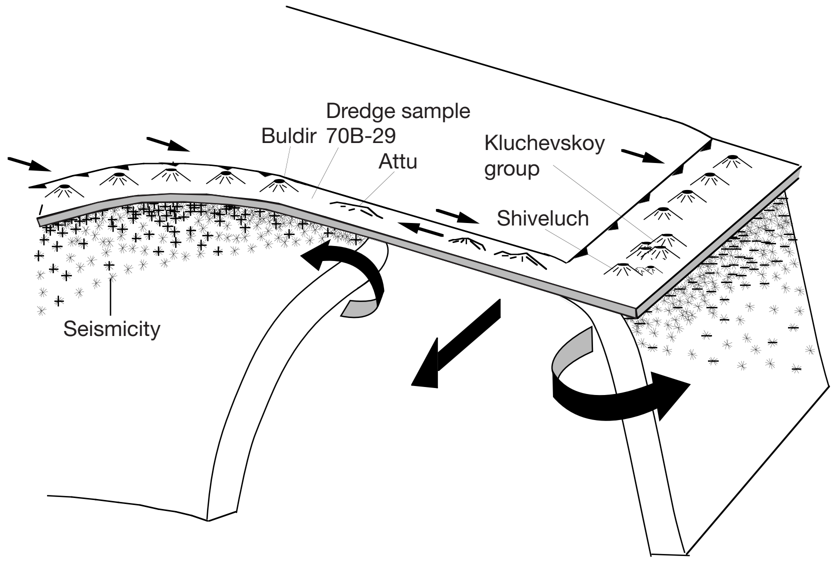

Figure 5 Perspective drawing showing a torn Pacific plate subducting to the north beneath the central Aleutians (Adak) and to the west beneath Kamchatka. The geometry shown here implies that the Pacific plate is being torn in an unzipping motion as the Aleutian slab sinks to the north beneath the Bering Sea. Adakitic volcanism is observed at Sheveluch volcano, immediately above the torn plate edge beneath Kamchatka, and above the inferred position of the active tear in the Pacific plate beneath the western Aleutians (location of andesite sample 70-B29). The large arrows indicate asthenospheric flow around the plate edges and through the slab window. This kind of mantle flow would explain the melting of relatively old subducting plates along their edges, as well as the relatively high heat flow from the area of the Komandorsky basin in the western Bering Sea (location in Fig. 1). Asterisks indicate the seismicity (schematically) which shoals to the north beneath Kamchatka (Fig. 2) and to the west beneath the Aleutians.

In this case we expect adakite genesis through melting of the leading edge of the Australian plate as it enters warm asthenosphere beneath the Pacific plate.

The Aleutian, Kamchatkan and other examples cited here emphasize that adakite genesis is linked to unusual conditions in the subducting plate that are produced not only by slab age[5], but also by slab geometry. The wide geochemical variation in the western Aleutian–Kamchatka region (Figs 3, 4) suggests that in general, arc magmatism may exist on a continuum between relatively hot mantle systems, which are dominated by primary basalt (for example, Klyuchevskoy), and hot slab systems, which are dominated by relatively cool and hydrous primary andesite (for example, Sheveluch). In this view, adakites with Mg number (Mg#) greater than 60 (Fig. 4b) represent the extreme case of primitive arc magmatism in a hot slab system. Relatively low magmatic output of such systems (for example, western Aleutians[23,24], southwest Japan[25,26]) may result from dehydration of the slab at shallow depths[26], or from the cooling of the mantle wedge by slab-derived melts. Endmember hot-slab and hot-mantle systems will generally also show contrasting seismicity and seismic structure[26]. This view of arc magmatism underlines the need to improve our understanding of subduction dynamics and the physical conditions of the slab and mantle wedge, and their connection to primary magma geochemistry in a variety of subduction settings. □

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A bizarre predatory dinosaur from the Late Cretaceous of Madagascar

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Here we report the discovery of a small-bodied (~1.8 m) predatory dinosaur from the Late Cretaceous (Maastrichtian) of Madagascar. *Masiakasaurus knopfleri*, gen. et sp. nov., represented by several skull elements and much of the postcranial skeleton, is unique in being the only known theropod with a highly procumbent and distinctly heterodont lower dentition. Such a derived dental morphology is otherwise unknown among dinosaurs. Numerous skeletal characteristics indicate that *Masiakasaurus* is a member of Abelisauroidea, an enigmatic clade of Gondwanan theropods. Previously, small-bodied abelisauroids were known only from Argentina[1–3]. The occurrence of *Masiakasaurus* on Madagascar suggests that small-bodied abelisauroids, like their larger-bodied counterparts, were more cosmopolitan, radiating throughout much of Gondwana and paralleling the diversification of small coelurosaur theropods in Laurasia.

Several expeditions[4–7] have recovered abundant, well-preserved skeletal remains of dinosaurs and other vertebrates from the Upper Cretaceous (Maastrichtian) Maevarano Formation of northwestern Madagascar. The non-avian dinosaur fauna includes a large abelisaurid theropod, *Majungatholus atopus*[5], and at least two titanosaurian sauropods. Remains of at least five species of birds have also been recovered, including the basal avian *Rahonavis ostromi*[7]. Our study describes a previously unknown small-bodied form recovered from the same deposits.

Saurischia Seeley 1888
Theropoda Marsh 1881
Abelisauroidea Bonaparte 1991
Masiakasaurus knopfleri gen. et sp. nov.

Etymology. From *masiaka* (Malagasy, meaning vicious), *sauros* (Greek, meaning lizard) and *knopfleri* (after singer/songwriter Mark Knopfler, whose music inspired expedition crews).

Holotype. Université d'Antananarivo (UA) 8680, well-preserved right dentary with several teeth (Fig. 1).

Referred specimens. Field Museum of Natural History (FMNH PR 2108–2182): maxilla; dentaries; splenial; cervical, dorsal, sacral and caudal vertebrae; dorsal rib; humeri; manual phalanges and ungual; pubes; femora; tibiae; tibia/fibula/astragalocalcaneum; metatarsals II and III; pedal phalanges and unguals. UA 8681–8696: dentary; cervical, dorsal, and caudal vertebrae; femora; tibia/astragalocalcaneum; pedal phalanges; and unguals.

Localities and horizon. All specimens are from the Anembalemba Member of the Upper Cretaceous (Maastrichtian) Maevarano Formation, Mahajanga Basin, near the village of Berivotra, northwestern Madagascar[8]. With few exceptions, elements attributable to *Masiakasaurus*, including the holotype dentary (UA 8680), were recovered as isolated specimens from a 3-m^2 area in one stratigraphic horizon of a single locality, MAD 93-18.

Diagnosis. Differs from all known theropods in that the four dentary teeth most rostral in position are procumbent, with the first tooth set in a large, ventrally expanded alveolus that is almost horizontal in orientation. Also differs from all known theropods in that it has a strongly heterodont lower dentition: the first four teeth are elongate and weakly serrated, with labiolingually positioned carinae. Each of these four teeth terminates in a pointed apex that hooks caudally. The teeth become increasingly recurved and transversely compressed with increasing caudal position in the jaw, and possess more standard, mesiodistally positioned carinae.

Description. Together, the specimens referred to *Masiakasaurus knopfleri* account for about 40% of the skeleton (Fig. 1). The concentration of isolated *Masiakasaurus* elements at MAD 93-18 includes remains of at least six individuals. All of these specimens are assigned to a single species, despite many of the elements (for example, femora, tibiae and vertebrae) being represented by several specimens, as none shows evidence of belonging to more than one taxon of small-bodied non-avian theropod. Two osteological features (closure of the vertebral sutures and fusion of the crural and tarsal elements) indicate that the largest materials represent adult or near-adult individuals of this small-bodied taxon.

The maxilla, which is represented by a single partial specimen (Fig. 1; FMNH PR 2183), has a pronounced, raised external rim forming the perimeter of the extensive antorbital fossa. Although lacking accessory foramina, a deep accessory fossa occupies the rostral portion of the antorbital fossa. Seven alveoli are preserved and, although a small portion of the caudal alveolar margin is missing, it is unlikely that the maxillary tooth count exceeded ten. Unerupted teeth, which are preserved in the third and fifth alveoli, are transversely compressed, recurved and bear moderate serrations. Although the first tooth is absent—and thus the crown orientation cannot be determined with confidence—the first alveolus is oriented at about 45° to the horizontal, indicating that the rostrally positioned teeth in the upper jaw may have been procumbent.

The specialized dentary (Fig. 2), represented by four specimens, has a greatly emarginated caudal end that indicates an enlarged intramandibular fenestra, as in Abelisauridae. The number of tooth positions in the dentary of *Masiakasaurus* varies from 10 to 12. The slightly enlarged first alveolus is oriented almost horizontally to such an extent that the first tooth is directed forward. The first four teeth are radially arrayed, and become progressively more vertical and parasagittal with increased caudal position.

The bizarre morphologies of these first four teeth are unique among theropods. The caudal carina is labial (lateral), whereas the

