RESEARCH ARTICLES

Evidence for Persistent Flow and Aqueous Sedimentation on Early Mars

Michael C. Malin* and Kenneth S. Edgett

Landforms representative of sedimentary processes and environments that occurred early in martian history have been recognized in Mars Global Surveyor Mars Orbiter Camera and Mars Odyssey Thermal Emission Imaging System images. Evidence of distributary, channelized flow (in particular, flow that lasted long enough to foster meandering) and the resulting deposition of a fan-shaped apron of debris indicate persistent flow conditions and formation of at least some large intracrater layered sedimentary sequences within fluvial, and potentially lacustrine, environments.

The distribution in space and time of liquid water on Mars (*1–4*) remains unresolved, despite an increasing base of observational data about its influence on geological materials. In part, this gap in our knowledge arises from the lack of direct observation of the attributes of sedimentary rocks and deposits that best record their mode and environment of origin: the size, shape, and composition of constituent clasts, and the composition of any chemically precipitated materials. It also arises in part from the paucity of small-scale landforms generally diagnostic of the processes of emplacement. We report here the discovery of a landform complex whose location, planimetric and topographic form, structure, and erosional expression are characteristic of such processes and uniquely reflect materials deposited within an aqueous sedimentary environment.

Setting. The features were discovered in high-resolution (1.4 to 6.0 m/pixel) images acquired by the Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC) (*5–7*). Located in the Erythraeum region of Mars, the landform complex is associated with valleys that traverse the intercrater plains north of Holden Crater (26°S, 34°W, 150 km in diameter) and enter an unnamed crater, 65 km in diameter, located northeast of Holden at 24.3°S, 33.5°W (hereafter Holden NE Crater; Fig. 1). In addition to MOC images, pictures from the Mars Odyssey Thermal Emission Imaging System (THEMIS) (*8, 9*) and the Viking orbiter cameras were used to place the higher resolution MOC observations within their regional context, and MGS Mars Orbiter Laser Altimeter (MOLA) (*10*) data were used to determine the regional and local topography.

The region north of Holden Crater shows attributes of a "textbook" drainage basin, with 10 or more valleys contributing to a trunk valley that enters Holden NE Crater through its low, western wall (Fig. 1). The valleys of this drainage system exhibit several characteristics, including steep-walled, flat-floored, box-shaped transverse cross sections, nearly uniform width over most of their longitudinal course, irregular variations in depth (leading to stepped longitudinal profiles with occasional convex segments), abrupt distal terminations, and few if any higher order tributaries. These characteristics suggest immature drainage, or—more likely, given its size, extent, and geologic context—a drainage system that is partly buried and partly exhumed. The valleys "drain" an area of about 4000 km^2.

Distributary fan. At the distal end of the drainage system, within the western portion of Holden NE Crater, is a complex of layered sedimentary rock and a fan-like landform (*11*) consisting of a suite of sinuous ridges (Fig. 2). The fan-shaped landform, which is 13 km by 11 km and covers 115 km^2, consists of at least three lobes, defined planimetrically by cross-cutting ridges raised above intervening smooth areas, together standing above the surrounding intracrater plain. The ridge complex has a low longitudinal gradient [$<0.35°$ (*12*)], a flat transverse section, and a relatively steep distal front. Three relations within these lobes are especially noteworthy: (i) the sinuous, meandering nature of the ridge forms, in particular the appearance of ridges resembling migrating and cutoff meanders (Fig. 2A); (ii) the expression of three-dimensional stratigraphic relations, as seen in the cross-cutting of ridges and their interfingered position with respect to light-toned, flat-lying strata (Fig. 2B); and (iii) a hierarchical size–planimetric position–stratigraphic relation with narrow, gently sinuous, distal ridge forms lower in the sequence and larger, more broadly sinuous proximal ridge forms higher in the sequence.

We interpret the landform in Holden NE Crater to be the exhumed and/or eroded remnant of a fluvial distributary fan. The sinuous ridge forms are interpreted to result from relief inversion of channels (*13*), and the

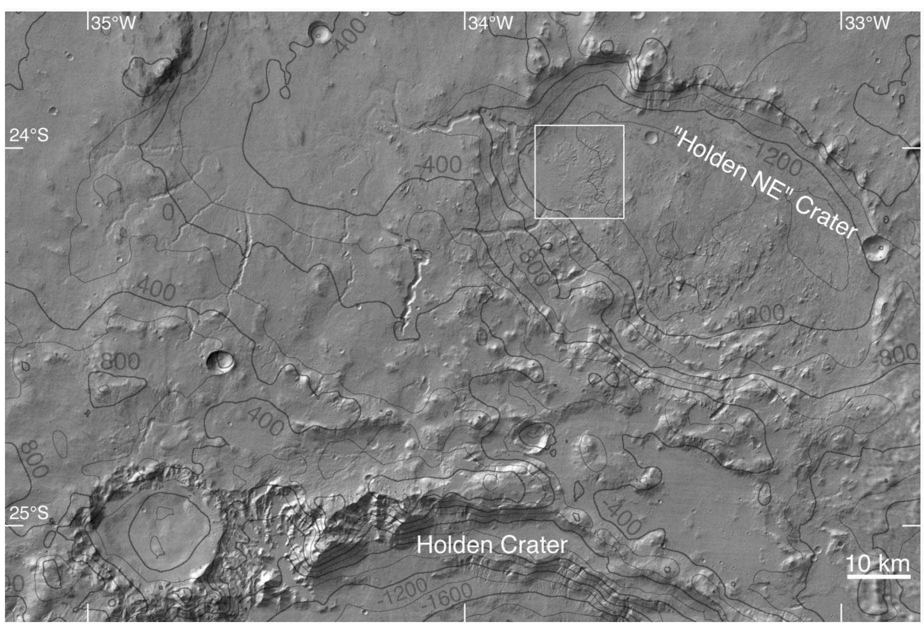

Fig. 1. Regional setting of Holden NE Crater, Erythraeum region, Mars. Map base is a mosaic of portions of THEMIS IR images I01737002, I01762002, I02461003, I03185002, I03210002, I03572002, I03597002, I04733002, and I04758002, in simple cylindrical projection at 48 m/pixel. Topography, derived from MOLA data and relative to the martian datum, is shown in 200-m contours, with alternate contours (400 m) denoted with thicker lines. The white box indicates the location of Fig. 2.

Malin Space Science Systems, Post Office Box 910148, San Diego, CA 92191, USA.

*To whom correspondence should be addressed.

cross-cutting, stratigraphic, and size-position relations are interpreted as evidence of progressive or progradational (*14*) fluvial activity and emplacement of alluvial sediments. Longitudinal and transverse variations in some of the ridges (such as the proximal-to-distal variation in channel width, as manifested by meander migration) suggest heterogeneity within the materials, with proximal patterns reminiscent of terrestrial channels with a substantial component of coarser materials (sand or gravel, which permit wider, broader meanders to develop) and distal patterns showing narrower channels with gentler meanders suggestive of more homogeneous, possibly smaller caliber materials. Along the distal margins and as seen in erosional windows within the lobes, individual inverted channels grade into and are interbedded with broader, thinner, mostly horizontal, light-toned layers. Occasional outcrops of light-toned rock and isolated, inverted-relief channel segments (e.g., MOC images R07-00821 and R07-01352) with similar erosional expression elsewhere in Holden NE Crater suggest that units once more areally extensive have been stripped away, except where the upper fan materials have acted to protect and preserve them. The 6 km^3 volume of the fan (overestimated because of the difficulty in measuring the many erosional depressions smaller than the MOLA data can resolve) is about one-quarter of the exposed volume of the valleys that fed it.

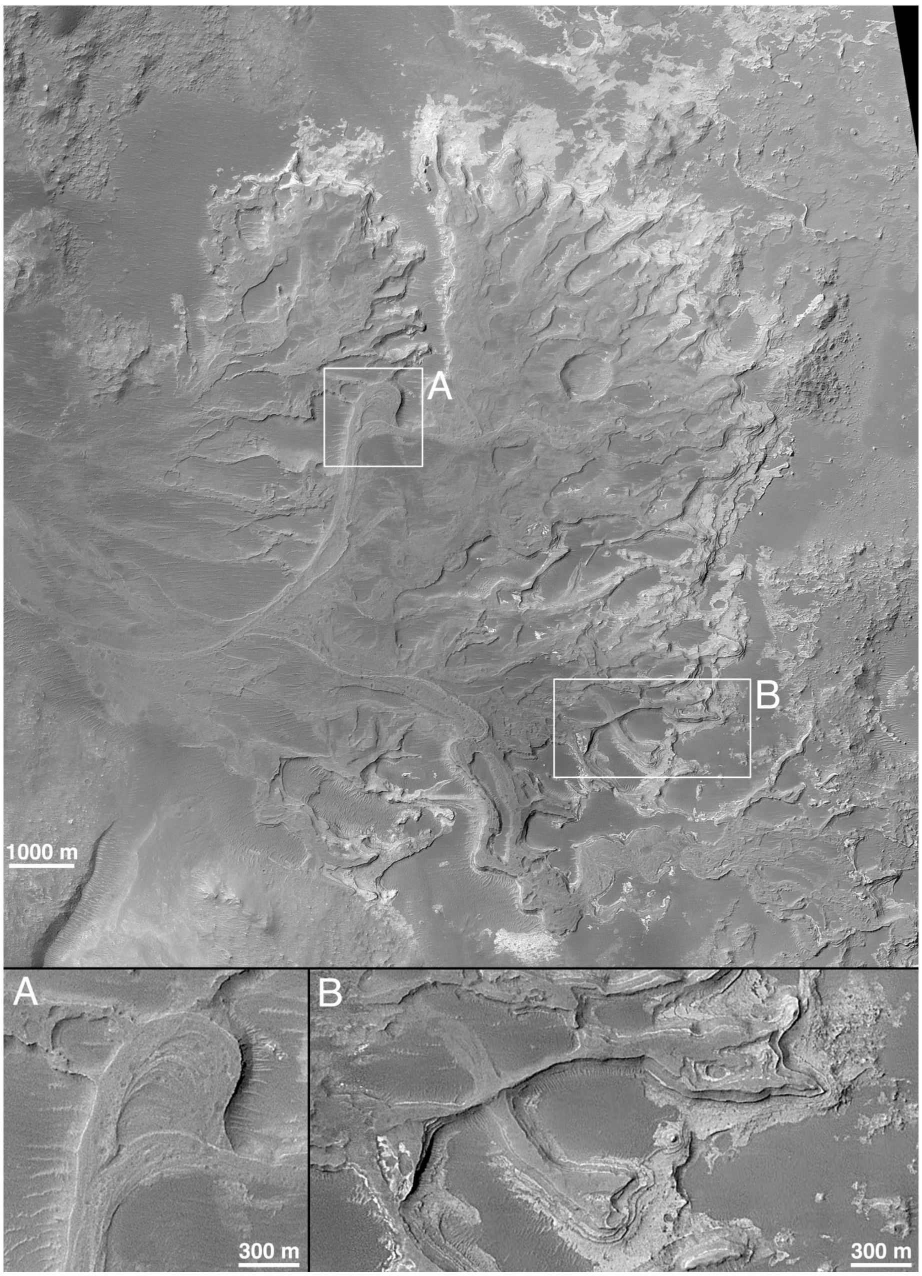

Fig. 2. Fan in Holden NE Crater. The main figure is a mosaic of portions of MOC images M18-00020, E14-01039, E17-01341, E18-00401, E21-01153, E21-00454, E22-01159, E23-00003, R06-00726, R08-01104, and R09-01067 in simple cylindrical projection at 3 m/pixel, showing a three-lobed fan of ridge forms interpreted to be inverted channels. (**A**) Pattern of migrating and cutoff meander of relief-inverted channel. (**B**) Superposition and cross-cutting relations between two inverted channels and their deposits. Right side of (B) shows inverted channels merging with layered materials seen in many other portions of the floor of Holden NE.

Implications. Three important issues in martian geological studies are addressed by the discovery of this landform: flow persistence, formation of water-lain sedimentary deposits (with implications for both longitudinal transport of material through a martian fluvial system and directly related and explicit evidence of alluvial deposition), and the intimate relation between materials directly linked to stream transport and more broadly distributed layered materials. In addition, some attributes of this landform more speculatively address the issue of bodies of standing water.

The question of whether water flowed across the surface of Mars for long periods of time has been debated since martian valley systems were first discovered (*15*). With the exception of a few examples based on large-scale planimetric patterns [e.g., the interpretations of the sinuosity of Nirgal Vallis as evidence of meandering (*16*)], most evidence has been interpreted as indicating that water moved across the surface in relatively short, intense outbursts [i.e., forming outflow channels by catastrophic flooding (*17–19*)] or ephemeral trickles of groundwater-fed base and seepage flow [forming substantially smaller, relatively tributary-free valleys (*19, 20*)]. The best evidence for long-term persistent flow is provided by the tight sinuosity and deep entrenchment of a few valleys (e.g., Nanedi and Scamander valles) and the occasional emergence of smaller, leveed channels from beneath the colluvial debris covering their floors. However, any answers to critical questions—such as where the water came from, whether such flow was continuous or episodic, and how long it took for a 100- to 200-m-wide stream to cut a canyon 800 km long, 3 km wide, and 1 km deep—remain highly speculative. The fan in Holden NE Crater presents unequivocal evidence of persistent flow in the form of evolving meanders. Although it is not possible to establish the duration of the flow, the conditions that create meanders require time and continuity to permit the geometry to develop and evolve (*21*).

The argument that water has played a major role in eroding and transporting materials on Mars can be challenged by citing the difficulty in identifying any unequivocal evidence of the deposits that must have formed if such transport occurred. Three factors contribute to this challenge: our inability to see diagnostic features of alluvial deposits associated with most large outflow channels and valley networks; the existence of equally plausible, alternative interpretations for the generally rare deposits found where valleys enter craters or irregular intercrater depressions (*22*); and the absence of a direct connection between valley systems and the exposures of layered rock found in numerous locations ranging from equatorial sites within the Valles Marineris and craters of Arabia Terra to intracrater occurrences in mid- to high southern latitudes (e.g., Spallanzani Crater).

The fan in Holden NE Crater has manifested more characteristics of fluvial erosion, transport, and deposition than any previously observed landform on Mars, as judged by its position at the distal end of a network of valleys, the specific imprints of the channels seen on its surface, and the pattern of evolution of these channels over time as revealed through erosion. The interbedding of light-toned, flat-lying layered rock units with the fan further strengthens the impression that this location records the entire "life cycle" of sedimentary materials: headwater erosion, through-basin transport, alluvial deposition, induration/lithification, and, ultimately, secondary erosion and exportation of fines, creating a residual, exhumed landscape. That all of these events occurred suggests that the landform complex is extremely ancient, as it must date to a time in martian history when persistent water flow could occur, after which sufficient time must have elapsed for the materials to be lithified and later eroded/exhumed to their present state. Although it is impossible to date martian surfaces from impact craters in either an absolute or relative sense, given the problems of burial and exhumation, martian valley networks and their associated fluid flow are generally acknowledged to represent attributes of early, or Noachian, Mars [e.g., (*2*)].

The search for evidence of past bodies of standing water on Mars has gained importance in recent years because of its direct relevance to NASA's objectives in astrobiology. We believe that evidence developed from the interpretation of Viking Orbiter images—in particular the identification of and differentiation between "fans," "fan-deltas," "Gilbert deltas," and "deltas"—is equivocal (*22*). We cannot state with certainty that the Holden NE fan resulted from deposition to maintain and adjust base level (a defining characteristic of a delta) where the water conducted through the valleys to the west entered and ponded within the crater, but there are tantalizing hints that this indeed may have been the case. To the extent that the information can be gleaned from MOLA measurements (and recognizing that the details are blurred by other processes), the longitudinal profiles of both valleys that fed the Holden NE fan are steep and characteristically concave as they descend into the crater, but transition over a very short distance to be nearly flat as they connect to the profile across the fan. The declivity of the fan surface itself is very low, and the distal and lateral margins are steeper. The multilobate form of the fan, and variations within each lobe, mimic terrestrial deltas that avulsed during formation. Finally, it has been posited that laterally continuous, rhythmically layered (*23*), essentially horizontal rock units on Mars may have formed by deposition from standing water (*6, 24*). The intimate relation between the Holden NE fan and stratified units within the same crater is consistent with that view.

References and Notes

1. The debate over whether liquid water or some other fluid (including gas-fluidized dry flow) is responsible for erosional landforms on Mars (which include but are not limited to the martian outflow channels, valley networks, and gullies) is not specifically addressed in this work. Most geoscientists familiar with martian landforms agree that water is the most likely candidate fluid.
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3. V. R. Baker *et al.*, in *Mars*, H. H. Kieffer, B. M. Jakosky, C. W. Snyder, M. S. Matthews, Eds. (Univ. of Arizona Press, Tucson, AZ, 1992), pp. 493–522.
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7. MOC consists of three cameras: one high-resolution, narrow-angle telescope, and two wide-angle cameras for low-resolution global and regional monitoring. A description of the experiment can be found in (*5*); results from the first Mars year of MOC operations are presented in (*6*). As of 21 October 2003, 155,000 images have been acquired by the MOC, of which nearly half are at scales of 1.4 to 12 m/pixel. Approximately 3% of the planet's surface area has been imaged at these scales.
8. P. R. Christensen *et al.*, *Science* **300**, 2056 (2003).
9. In general, images of surfaces taken at other than visible wavelengths should be used cautiously for geomorphic interpretation because of characteristics that may arise from the behavior of surface materials at those wavelengths. A "bright" feature in an infrared (IR) image is hot, not light-toned; indeed, because dark-toned features on planetary surfaces will be warmer than light-toned features during daytime hours (all other factors being the same), an IR image would be anticorrelated with albedo. Nighttime IR images show mostly differences in how areas retain heat after sunset, and are thus a measure of thermal inertia (which depends on the density, heat capacity, and thermal conductivity of the materials). However, the primary factor affecting temperature during the day is the declivity and azimuth of the surface slope. Daytime IR images look for the most part like shaded relief representations of the surface, with slopes that receive direct solar heating being warmer, and therefore brighter, than slopes that face away from the Sun. Such images are nearly ideal for geomorphic studies.
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11. For the purposes of discussion, we define a fan as any accumulation of debris transported by fluvial processes under laterally constrained conditions and deposited in the absence of that constraint. In this broad definition, a delta would be a subclass of fan in which rapid deposition of fluvially transported material occurs as a subaerial flow attempts to maintain and adjust its base level upon entering a body of water. We acknowledge that this and many other classification schemes [e.g., (*25–27*)] fail to capture the range and complexity of depositional environments found on Earth, and that inferences derived from any of the alternative schemes used to classify terrestrial fans and deltas [for example, that subaerially deposited materials tend to have steeper longitudinal slopes than those deposited in lacustrine or marine environments (*27*)] may be of limited applicability to martian studies.
12. MOLA measured the mean relief of spots about 150 m in diameter spaced about 300 m along the MGS orbit ground track from March 1999 through June 2001. Ground track separation was not systematically controlled, hence coverage is not uniform. Laser altimetry for the region north and east of Holden Crater was converted to digital elevation models (DEMs) with the GMT software package (*28, 29*). Gridded and contoured products were produced using programs *blockmedian*, *surface*, and *grdcontour* with ground sampling increments of 48 m. The DEMs were converted to grayscale images and coregistered with MOC and THEMIS mosaics. Topographic profiles were located on the images and the corresponding relief values determined from the DEMs.
13. Inversion of relief occurs by denudation in cases where a material that once was at the floor of a channel or depression—either intrinsically more resistant to erosion (e.g., coarser grained) or rendered more resistant by cementation—forms an armor that protects underlying materials from removal (in volcanic settings on Earth, lava may flow down a preexisting valley or into a depression, thus forming an erosion-resistant unit that can likewise protect underlying materials, although this is not what occurred in Holden NE Crater). The surrounding, less resistant materials are eroded away, and the former depression or channel floor then stands higher than surrounding terrain. Burial, exhumation, and inversion of relief are common attributes of martian geology (*6*), and numerous examples of inverted channels have been identified in MOC and THEMIS images; examples are located in northeast Arabia Terra near 32°N, 314°W (MOC images M15-00823, M20-00098, R09-00568, R09-01403, R09-02724, R09-03590, and R10-01078), southeast Arabia Terra near 11°N, 313°W (THEMIS image I01646005), southwest of Juventae Chasma near 4°S, 63.5°W (MOC images R07-00999, R08-02192, R09-00590, R09-01445, R09-02851, R09-03652, R09-04056, and R10-01114; THEMIS images V05558002 and V06307001), and south-central Arabia Terra near 7°N, 343.5°W (MOC images M10-03450 and R05-03450; THEMIS image V07257022). In addition, a fan-like pattern of exhumed, inverted channels exhibiting some of the cross-cutting and meander characteristics of the Holden NE Crater complex is located in Aeolis near 6.5°S, 209°W (MOC images FHA-00772, M00-02962, M02-02414, M03-02792, M20-01792, M21-00360, E05-02402, E13-01135, E18-00307, and R10-03569; THEMIS image V05588002). Relief-inverted paleochannels described in this paper and at the other martian locations listed above are strikingly similar to those found in central Saudi Arabia (*30*) and eastern Oman (*31*).
14. We use the term "progressive" to mean that emplacement occurred both in a specific, sequential manner (e.g., in which lower, smaller distributaries were covered by later, larger distributaries) and by advancing distally.
15. As summarized more than two decades ago by the Mars Channel Working Group (*32*) and further amplified by Carr and Malin (*20*) using MGS data, characteristics of martian landforms are often ambiguous on the subject of how much fluid was involved in their formation, how it moved, and over what time scales. At large scale, valley networks appear to have the ramified pattern of integrated, contributing fluid and debris transportation systems, but higher resolution views show these networks to lack the smaller, lower order tributaries seen in most terrestrial river systems that occur as a natural consequence of overland flow. They instead more closely resemble terrestrial systems in which groundwater—both in the form of wall seepage and as base flow into small streams substantially underfit to the valleys in which they occur—controls valley development by undermining and collapse of valley headwalls and sidewalls. Such groundwater-related processes still require surface flow and a level of persistence necessary to break down and remove material derived from the walls, but the discharge rates and volumes can be substantially smaller and occasional rather than perennial.
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20. M. H. Carr, M. C. Malin, *Icarus* **146**, 366 (2000).

21. Despite the absence of key information about sediment caliber, stream load, original gradients, and original basin morphometry that would be needed to perform a quantitative assessment of the hydrology of the Holden NE basin, it is somewhat informative to examine those aspects of the system for which some reasonable assumptions can be made. The relatively low gradient (0.35°) of the well-exposed meander zone seen in Fig. 2A, and the measurement of a typical channel width of 50 m, permits the calculation of flow velocity using the Manning equation with appropriately gravity-modified parameters (*33*) if one assumes a range of possible flow depths and Manning roughness coefficients. For values of roughness corresponding to 0.04 on Earth (a bed mostly of fine-grained materials but with some stones), flow depths of a few meters on Mars would flow at a few meters per second, producing discharges of a few hundred cubic meters per second. Terrestrial field experience suggests that this rate is consistent with the size and configuration of the meanders seen (although perhaps on the high end of such an estimate). Were this discharge to occur today, it would fill the existing, eroded floor of Holden NE Crater to the –1300 m level (the level at which both major valleys entering the crater lose definition) in roughly 20 years. Although fraught with uncertainties owing to dependencies on climate, catchment basin size and geometry, and lake volume, the Holden NE values fall within a range that includes comparable desert environment lakes such as the Great Salt Lake in Utah and the Sea of Galilee (inflow rates of tens to hundreds of cubic meters per second, lake volumes of 10^9 to 10^{11} m^3, and filling times of decades). These calculations simply show that the relations are internally consistent with similar relations seen on Earth, not necessarily that the situations are identical.
22. As part of our study, we targeted 158 locations identified by previous investigations [e.g., appendix B in (*34*)] as potential "alluvial fans" and "deltas" (*34, 35*) and more than 100 additional locations exhibiting similar topographic relations (valleys entering depressions). As of October 2003, some 200 MOC images covering approximately 80 locations had been acquired and inspected. All of these images show features quite different from those discussed in this work, generally falling into two categories. The most prevalent category is one in which the floors of the valley and crater are concordant, showing no discernible expression of deposition (e.g., MOC images E04-01284, E23-01302, and R02-00995). In these cases, alluvial deposits may exist but have been buried by some process that filled the crater, or may have once existed but have since been completely stripped away. In a relatively small number of cases (the second category), a discernible apron of material is seen at the point where the valley enters the crater. Although the aprons have some attributes of alluvial fans (they are conical in three-dimensional form, have longitudinal slopes ≥2° and convex transverse sections, and occur adjacent to high-standing relief), they have three characteristics that distinguish them from the fan described in this work: They consist of a single (rather than multiple) lobe of material, they lack a radial (or distributary) pattern of conduits, and they display concentric steps in their surface's descent to the crater floor (e.g., MOC images E02-00508 and R02-00093). The concentric steps are unique to the aprons, as the adjacent crater walls do not display such forms (that is, the steps are not wave-cut terraces). In some cases, the volume of the apron appears to be equal to the volume of the valley (e.g., MOC images E05-02330, E09-00340, and E11-00948). These aprons appear to be the result of mass movements rather than fluvial processes, with the concentric steps resulting from successive surges of the material as it moved out of the valley or, more likely, as the expression of compressive stress in the material as it came to rest within the crater.
23. We use the term "rhythmically layered" to denote a sequence of tens to hundreds of repeated layers (or packages of layers too fine to resolve in MOC images) of essentially identical thickness and outcrop expression.
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An Early Cretaceous Tribosphenic Mammal and Metatherian Evolution

Zhe-Xi Luo,[1,2]* Qiang Ji,[2,3] John R. Wible,[1] Chong-Xi Yuan[4]

Derived features of a new boreosphenidan mammal from the Lower Cretaceous Yixian Formation of China suggest that it has a closer relationship to metatherians (including extant marsupials) than to eutherians (including extant placentals). This fossil dates to 125 million years ago and extends the record of marsupial relatives with skeletal remains by 50 million years. It also has many foot structures known only from climbing and tree-living extant mammals, suggesting that early crown therians exploited diverse niches. New data from this fossil support the view that Asia was likely the center for the diversification of the earliest metatherians and eutherians during the Early Cretaceous.

Marsupials are one of the three main lineages of extant mammals (Monotremata, Marsupialia, and Placentalia) (*1, 2*). Extant marsupials, such as the opossum, kangaroo, and koala, are a subgroup of the Metatheria, which also includes all extinct mammals that are more closely related to extant marsupials than to extant placentals (*3*). Both metatherians and eutherians (including extant placentals) are subgroups of the northern tribosphenic mammal clade or Boreosphenida (*2, 4, 5*). Here we report a new boreosphenidan mammal with close affinities to metatherians, and discuss its implications for the phylogenetic, biogeographic, and locomotory evolution of the earliest eutherians and metatherians.

Sinodelphys szalayi (*6*) gen. et sp. nov. is distinguishable from all mammals (*7–11*) previously known from the Yixian Formation [125 million years ago (Ma) (*12*)] by a long list of apomorphies (*13, 14*). Numerous dental and skeletal apomorphies also distinguish *Sinodelphys* from all Cretaceous eutherians (including *Eomaia* from the Yixian Formation) (*2, 10, 15–18*). *Sinodelphys* is also more derived than the stem boreosphenidans (*4*) outside the therian crown group (metatherians + eutherians) in several dental apomorphies, but is less advanced than other metatherians including *Deltatheridium* (*3*) in dental formula (*13, 14*). Hairs are preserved as carbonized filaments and impressions around the torso of the holotype (Fig. 1). The pelage appears to have both guard hairs and denser underhairs close to the body surface.

Description and comparison. *Sinodelphys szalayi* is more closely related to extant marsupials than to extant placentals and stem taxa of boreosphenidans in its many marsupial-like apomorphies in the skeleton and anterior dentition (Fig. 1). The posterior upper incisors (I3, I4) are mediolaterally compressed with an asymmetrical, lanceolate (nearly diamond) outline in lateral view. This feature is characteristic of "didelphid-like" marsupials and the stem metatherians for which incisors are known (*19–24*), but it is absent in all known Cretaceous eutherians and mammals outside crown Theria (*7, 10, 25–27*). The first upper premolar (P1) is procumbent and close to the upper canine, fol-

[1]Carnegie Museum of Natural History, Pittsburgh, PA 15213, USA. [2]Department of Earth Science, Nanjing University, Nanjing 200017, China. [3]Chinese Academy of Geological Sciences, Beijing 100037, China. [4]China University of Geosciences, Beijing 100083, China.

*To whom correspondence should be addressed. E-mail: luoz@carnegiemuseums.org