the platinum container walls, and the aluminum oxide core surrounding the central heater.

8. Constant thermal properties used in the numerical modeling are as follows: density, 2630 kg/m^3; specific heat, 1255 J/kg-K; thermal conductivity, 1.255 W/m-K; and coefficient of thermal expansion, 4×10^{-5} K^{-1}.
9. Here Nusselt number is the experimental heat transfer coefficient divided by the heat transfer coefficient obtained from the numerical model for pure conduction. The experimental coefficient is a function of mean temperature and is given by

$$h = \frac{Q}{A(T_i - T_o)}$$

where Q is heater power, A is area of the inner wall of the crucible, and T_i and T_o are average inner and outer wall temperatures, respectively.

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Mesozoic Mammals from Arizona: New Evidence on Mammalian Evolution

Abstract. *Knowledge of early mammalian evolution has been based on Old World Late Triassic–Early Jurassic faunas. The discovery of mammalian fossils of approximately equivalent age in the Kayenta Formation of northeastern Arizona gives evidence of greater diversity than known previously. A new taxon documents the development of an angular region of the jaw as a neomorphic process, and represents an intermediate stage in the origin of mammalian jaw musculature.*

Knowledge of the emergence and early evolution of mammals has been based upon faunas of Late Triassic–Early Jurassic age from localities throughout the Old World (*1, 2*). Best known and most common are representatives of the Morganucodontidae, a family of triconodonts allied to later groups of Mesozoic mammals (*3*); morganucodontids are known from England and Wales, continental Europe, China, and southern Africa. Another family, the Kuehneotheriidae, is known solely from isolated teeth and fragmentary maxillae and mandibles found in fissure deposits in Wales; the molars nonetheless give evidence that *Kuehneotherium* was of the stock that gave rise to later therian mammals (*4*). Most other mammalian fossils of comparable age are too incomplete to establish their affinities with confidence (*5*). Until recently, we interpreted the major event of early mammalian evolution as a dichotomous branching of morganucodontids (nontherians) and kuehneotheriids (therians) during the latter half of the Triassic (*3*). In this report of the first discovery of a morganucodontid fauna in the New World, we also describe a previously unknown mammal, and present evidence that modifies previous interpretations of early mammalian anatomy and evolution.

The fossil mammals were discovered in the silty facies of the Kayenta Formation exposed along the Adeii Eechii Cliffs about 30 miles south-southeast of Tuba City, Arizona (*6*). The associated vertebrate fauna includes ornithischian and saurischian dinosaurs, crocodilians, tritylodontids, turtles, lizards, amphibians, and pterosaurs (*7*). Two taxa, the small tritylodontid *Oligokyphus* (*8*) and a morganucodontid, are congeneric with forms from European deposits.

The morganucodontid remains are fragmentary; they consist of a crushed skull, postcranial bones, and four isolated teeth. A well-preserved left upper molar (Fig. 1, a and b) shows the configuration of cusps *A–F*, and the presence of a large external and a smaller internal cingulum, all morganucodontid characteristics (*9*). The dimensions of the crown (length, 1.11 mm; width, 0.64 mm) are within the observed ranges of the Welsh morganucodontid *Morganucodon watsoni* and those of the Chinese species (*10*). However, several features of the Kayenta morganucodontid molar are distinctive. Cusp *B* is more robust than cusp *C*. The internal cingulum, which is typically complete in *M. watsoni*, has a hiatus at its midpoint. The large size of the cuspules on the external cingulum is more similar to that of the southern African *Megazostrodon* than to that of the Welsh morganucodontid. These features are probably indicative of a species difference, but for lack of more complete material at present we simply refer the Kayenta morganucodontid to *Morganucodon* sp.

One specimen may provide evidence of haramiyids, an enigmatic group of mammals [possibly ancestral to multituberculates (*11*)] that occurs as rare fossils in Rhaeto-Liassic deposits of Europe. The tooth (Fig. 1c) bears several features characteristic of *Haramiya*: two rows of cusps, joined at one end by a crest, enclose a central sulcus; one row bears three cusps; the largest cusp of the other row is adjacent to the open end of the sulcus, and there are three roots, two of which form a pair below the open end of the sulcus. Unlike *Haramiya*, however, the second row bears only two cusps (rather than four or five), and the tooth is smaller (0.66 mm long) than European specimens (1 to 3 mm) (*2, 12*). Haramiyids are insufficiently known to assess the significance of these differences, but their occurrence with *Morganucodon* strengthens the correlation with Rhaeto-Liassic vertebrate faunas of Europe.

More abundant and better preserved are specimens of a new mammalian taxon:

Class: Mammalia
Order: Triconodonta
Family incertae sedis
Dinnetherium gen. nov.

Etymology: Dinne, the Navajo Indian word for the (Navajo) people; Thērion, Greek, wild beast: the "Navajo's wild beast."

Type species: *Dinnetherium nezorum* sp. nov.

Diagnosis: As for the type and only species.

Dinnetherium nezorum sp. nov.

Etymology: Named for the Nez family of Gold Spring.

Type: MNA V3221, a partial right mandible with $M_{2\text{–}5}$.

Referred material: MCZ 20870–20877.

Diagnosis:

$$\mathrm{I}\frac{?}{4}\ \mathrm{C}\frac{?}{1}\ \mathrm{PM}\frac{2+?}{4}\ \mathrm{M}\frac{5}{5}$$

Three primary cusps on molariforms aligned anteroposteriorly as in morganucodontids, but central cusps *A*, *a* are taller as in *Kuehneotherium*. Adjacent molariforms interlock (Fig. 1) by cuspules *e* and *f* (*E* and *F*), forming an embrasure to receive the base of cuspule *d* (*D*) on the next anterior tooth. Cusp *a* occludes between *B* and *A* to produce a nearly horizontal, V-shaped facet that obliterates *B* in stages of advanced wear; cusp *A* produces a nearly vertical facet on *c*. The new species is distinguished from morganucodontids and *Kuehneotherium* by a flange-like ventrolateral extension of the lateral ridge of the dentary, and from triconodontids and amphilestids by the presence of a pseudangular process (*13*).

Dental occlusion and jaw movement, reconstructed from matching wear facets on associated mandibular and maxillary teeth, involved a combination of medial translation and rotation (*14*). Primary cusp *a* of lower molars was the first to make intercuspal contact, and wore be-

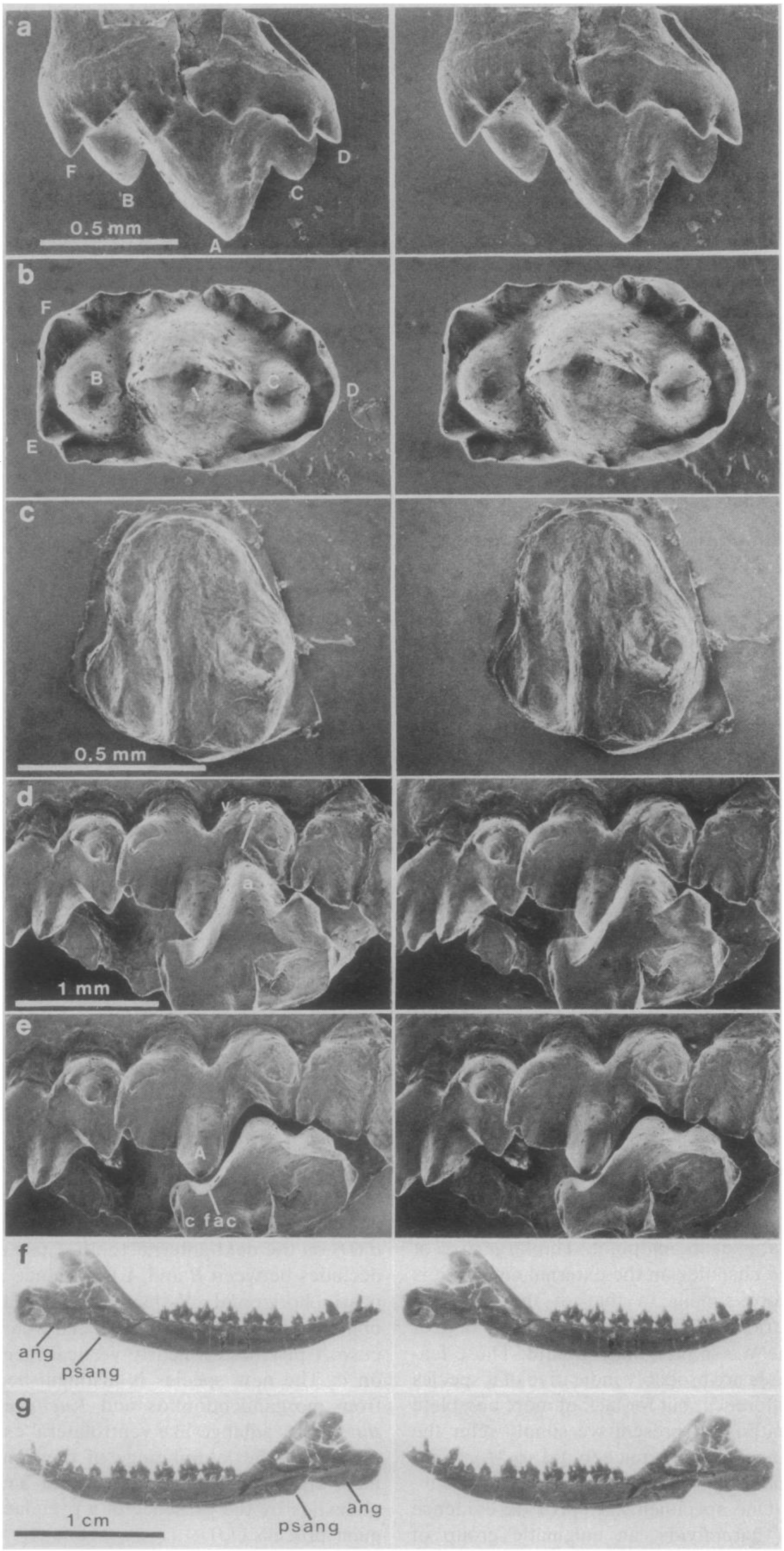

Fig. 1. Stereoscopic scanning electron micrographs (a to e) and photographs (f and g) of fossil mammals from the Kayenta Formation. (a) External and (b) occlusal views of an upper left molar of *Morganucodon* sp. (MCZ 20878). Cusp designations A to F after Crompton (9). (c) Occlusal view of a haramiyid molariform tooth (MCZ 20879). (d and e) Ventrolateral views of occlusal relations in *Dinnetherium nezorum* (upper right M^{234}, MCZ 20872; lower right molar, MCZ 20877) during initial (d) and subsequent (e) stages of jaw closure. (f) Lateral and (g) medial views of a lower jaw of *D. nezorum* (MCZ 20870) showing pseudangular (*psang*) and angular (*ang*) processes. The first, second, and fourth incisors are missing.

tween *B* and *A* of upper molars. As a result, *B* was obliterated in advanced stages of wear by the development of a deep, V-shaped facet (*v fac*, Fig. 1d). This facet extends from the external to the internal margins of the crown, evidence of substantial medial translation of the jaw during chewing (Fig. 1e). The orientation of the long axis of the "V" facet on $M^{3\ 4}$ of MCZ 20872 indicates that initially jaw movement was nearly horizontal (70° to 75° from vertical), and subsequently less so (60° to 65° from vertical). But the jaw also must have simultaneously rotated medially in order for primary cusp *A* of the upper molars, the next cusp to occlude, to wear a nearly vertical facet on the external side of *c* (*c fac*, Fig. 1e). On MCZ 20870, 20872, and 20877, the plane of the resultant facet varies between 14° to 21° with respect to vertical. Without medial rotation, the internal side of *A* fails to meet *c* along this plane.

The pseudangular process of cynodonts (advanced mammal-like reptiles from which mammals arose), morganucodontids, and kuehneotheriids is far anterior to the jaw joint. The homology of this process with the angle of the mammalian dentary, which is more or less below the jaw joint, has been accepted by several investigators, but questioned by Patterson (*15*). The pseudangular process is clearly present in *Dinnetherium* (Fig. 1, f and g), and as in other primitive mammals probably represents the truncation of the dentary associated with lateral exposure of persistently large postdentary bones (*16*). But *Dinnetherium* also has a bony flange in continuity with the masseteric fossa in the position of the angular region of later mammals (Fig. 1f). The flange is directed ventrolaterally (Fig. 1g), away from the postdentary bones that lie medial to it.

We conclude that the flange is a neomorphic angular region and that the mammalian angle, in this and possibly other lineages, did not originate through posterior growth of the pseudangular process. Experimental studies have demonstrated that the temporalis and superficial masseter rotate the mandible in forms that possess an elongate, nearly horizontal, mobile symphysis (*14*). In *Dinnetherium* the rugosity of the symphysis is indicative of a symphysial ligament, and the nearly horizontal orientation of its elongate outline (Fig. 1g) is evidence of mobility. Our interpretation of the wear facets as evidence for a combination of mandibular translation and rotation is corroborated by the nature of the symphysis, and by the angular flange that provides an attachment for a part of the masseter probably equivalent to the superficial masseter of modern mammals.

Dinnetherium documents an intermediate stage in the evolution of mammalian jaw musculature and movement, but in the development of an angular region it is clearly more advanced than previously known mammals of the time. The finding that *Sinoconodon* is a mammal (*5*), and the clear differences that distinguish *Dinnetherium* from contemporaneous taxa strengthen the view that Rhaeto-Liassic mammals were more diverse than previously thought (*17*). A simple dichotomy between morganucodontids (nontherians) and kuehneotheriids (therians) no longer appears to be an accurate representation of the complex, early evolution of mammals (*18*).

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5. A recently discovered skull of *Sinoconodon* provides definitive evidence that this form is a mammal, but the relation of the genus remains unclear (Sun Ai-lin and A. W. Crompton, personal communication).
6. The site (Gold Spring Quarry 1), in the middle of the Kayenta section, is located 35°45′47″N, 111°5′21″W, and approximately 1 mile west-southwest from Gold Spring (U.S. Geological Survey 7.5-minute topographic series, Gold Spring Quadrangle) on land of the Navajo Nation.
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13. *Dinnetherium nezorum* might be classified as an amphilestid on the basis of the familial diagnosis ("Premolars symmetrical and submolariform, molars more than four in number, with anterior and posterior cusps small relative to the main cusp"). But we believe that these primitive features do not adequately define the group, and the therian or nontherian affinities of amphilestids remain unclear.
14. Combined medial translation and rotation would have been necessary to effect the facets seen in the Jurassic triconodontid *Trioracodon*, and have been documented in a cineradiographic and electromyographic study (U. Oron and A. W. Crompton, unpublished data) of *Tenrec ecaudatus*.
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16. In an undescribed Chinese specimen of *Morganucodon*, the reflected lamina of the angular abuts the posterior margin of the pseudangular process (Sun Ai-lin and A. W. Crompton, unpublished data).
17. W. A. Clemens (*2*) expressed the opinion, based on studies of European material, "that Rhaeto-Liassic mammals can no longer be easily classified in just three families, Morganucodontidae, Kuehneotheriidae, and Haramiyidae."
18. We thank C. R. Schaff, W. W. Amaral, J. Attridge, J. Kirkland, S. Madsen, R. J. O'Hara, T. B. Rowe, K. K. Smith, H.-D. Sues, and H. E. Jenkins III for field assistance; W. W. Amaral and C. R. Schaff for laboratory preparation; E. Selig for scanning electron microscopy; A. H. Coleman for photography; L. L. W. Maloney for technical assistance; and W. A. Clemens for a review of the manuscript. The discovery of the first mammal specimens in 1980 (by W.R.D. and J. Kirkland) was facilitated by L. L. Jacobs and E. Hoyt, and financed by R. Downs. We thank the Navajo Tribal Council and the Coal Mine Mesa Chapter (T. T. Nez, president) for permission to conduct paleontological exploration on Navajo land, and the National Geographic Society for generous support of this research.

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Determination of Thermal Histories of Archeological Cereal Grains with Electron Spin Resonance Spectroscopy

Abstract. *The thermal histories of archeological cereal grains were examined by electron spin resonance spectroscopy. Studies with modern samples of heated cereal grain showed that the parameters of the electron spin resonance signal characterize the maximum temperature to which the sample had previously been heated. This technique has applicability in archeology and other disciplines.*

Although traces of the heating of an artifact or of fire in an archeological site can be important indicators of technological or cultural achievement, identification of such traces is often based on a subjective assessment of appearance. Errors in interpretations of ancient cultures and technologies will occur unless a sound basis can be established for ascertaining ancient thermal histories.

We have described how the effects of ancient heating of chert (*1*), bone (*2*), and ivory (*3*) can be identified by the detection of radical carbon with electron spin resonance (ESR) spectroscopy. Radical carbon is indefinitely stable (*1*) and gives rise to a readily observed ESR signal, which we have proposed as an indicator of previous heating. We have also noted that heating modifies transition metal (*4*) and organic (*5*) ESR spectra in chert, which points to other potential heat markers.

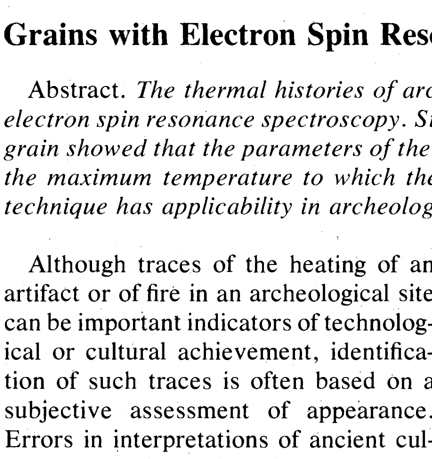

Fig. 1. Dependence of radical carbon *g* value on maximum temperature of previous heating for modern Emmer grains; the error of each *g* value measurement is ±0.0002.

We now report a study of cereal grains, which are widely encountered in archeological sites. The particular grain chosen was Emmer wheat (*Triticum dicoccum*) since it is found throughout Europe and southwestern Asia in sites ranging from the earliest Neolithic to late Classical times. Emmer grain was collected in northeast Turkey, where it is still under cultivation. Three archeological samples were studied: two of Emmer wheat and one of six-row barley. One Emmer sample, although slightly darkened, is in a state of nearly complete preservation through desiccation and comes from King Zoser's pyramid (Egypt, ~ 3000 B.C.). The other consists of blackened and brittle grains and comes from the immolation of the Mycenae granary (Greece, ~ 1100 B.C.). The six-row barley sample is from Wadi Kubbaniya, Egypt, and is of unknown date. It is blackened in appearance but retains its morphological characteristics.

Our experiments involved the measurement of values for the *g* factor, line widths (ΔH), and spin concentrations (c) of radical carbon ESR signals generated