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# THE MOENKOPI FORMATION IN EAST-CENTRAL NEW MEXICO: STRATIGRAPHY AND VERTEBRATE FAUNA

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**Abstract.**—The Anton Chico Member of the Moenkopi Formation in east-central New Mexico is 38-46 m thick and is divided into three main units that differ in bedforms, bed thickness and abundance of conglomerates. The following lithofacies can be distinguished: (1) floodplain siltstones, (2) fine- to medium-grained sandstones, probably deposited in broad channels, and (3) intraformational conglomerates with clasts of sandstone, siltstone and pedogenic concretions that mostly represent channel lags. Eight vertebrate-fossil-bearing levels are recognized; two of them are in sediments of ephemeral water bodies and yield articulated fossils of amphibians, whereas the other six levels represent intraformational, conglomeratic channel-fill deposits. One conglomeratic horizon is locally rich in isolated bones of amphibians and reptiles, and contains rare, well-preserved skulls. The Anton Chico fauna includes stereospondyl amphibians (*Eocyclotosaurus*, cf. *Stanocephalosaurus*), both known from the Holbrook Member of the Moenkopi Formation in Arizona, and archosauromorph reptiles (prolacertiforms, erythrosuchids, rauisuchians), which locally vary in abundance.

## INTRODUCTION

In east-central New Mexico, the oldest Triassic strata were originally referred to the Santa Rosa Formation (Rich, 1921; Darton, 1928). Gorman and Robeck (1946) divided the Santa Rosa Formation into four members, and made it clear that the lowest of these units is lithologically distinct, being composed of purplish-red instead of greenish-gray sandstones, and containing intraformational conglomerates in contrast to mixed conglomerates typical of the three higher members (Finch and Wright, 1983; Lucas and Hunt, 1987).

Lucas and Morales (1985) realized that the lowest member of the Santa Rosa Formation of Gorman and Robeck (1946) closely resembles the Holbrook Member of the Moenkopi Formation in northern Arizona. Lucas and Hunt (1987) thus removed the lowest member from the Santa Rosa Formation and referred it to the Moenkopi Formation, coining the term Anton Chico Member (originally a formation) for the east-central New Mexican facies.

Correlation of the Anton Chico Member with the Holbrook Member was established by the occurrence of the temnospondyl amphibian *Eocyclotosaurus*, the most characteristic vertebrate in the Anton Chico and Holbrook members (Lucas and Morales, 1985; Schoch, 2000), which is also known from the Upper Buntsandstein of central Europe (e.g., Kamphausen, 1989). Both the European and Arizona deposits are of Perovkan (early Anisian) age, suggesting a similar age for the Anton Chico Member (Lucas, 1998).

The stratigraphy, sedimentology and fauna of the Anton Chico Member are still poorly known, as only small outcrop areas have been briefly studied (e.g., Lucas and Hayden, 1989, 1991). A field project focusing on stratigraphy and vertebrate paleontology of the Anton Chico Member started in 1999, and is now being supported by the Deutsche Forschungsgemeinschaft. This article summarizes the current state of knowledge by presenting: (1) a detailed stratigraphy of the Anton Chico Member, discussing the vertebrate-bearing deposits; and (2) reporting briefly the recognized taxa from a study area that extends along the Pecos River from about Tecolotito to Colonias (Fig. 1)

## LITHOSTRATIGRAPHY AND VERTEBRATE-FOSSIL DEPOSITS

### Stratigraphic Section

The lithostratigraphy and sedimentology of the Anton Chico Member have not been studied in detail. We measured three complete sections that are between 38 and 46 m in thickness. The sites are (from east to west) southeast of Colonias, south of Anton Chico and north of Tecolotito (Fig. 1). Four additional partial sections cover the lower part, two sections the upper part, and several additional sections cover different parts of the member. A comparison of these sections reveals that the Anton Chico Member can be divided into three intervals.

In the lower interval, the Anton Chico Member consists of siltstones and fine-grained sandstones that may be horizontally laminated and contain rare calcrete-bearing paleosols in their basal part. Their top portion usually contains siltstone and fine-grained sandstone deposited in temporary floodplain ponds or lakes. The pond deposits are lithologically difficult to distinguish from surrounding floodplain deposits that contain coprolites and isolated amphibian bones (Fig. 2, level 5). The lake sediments are fine-grained, well laminated and devoid of vertebrate fossils. They contain subaquatically formed invertebrate tracks of the *Isopodichnus* type and wave ripples at their base (see Smith, 1993b for a similar case).

2. Fine- to medium-grained sandstones and rare coarse-grained sandstones either have indistinct bedding or trough cross-beds. Small-scale ripples are absent. Presumably, these strata formed in wide, rather shallow channels in low sinuosity river systems. Thin beds of this lithofacies may also represent crevasse channels and crevasse-splay deposits.

3. Intraformational conglomerates have clasts of fine sandstone, coarse siltstone and pedogenic calcrete. These beds often have an erosional base. Laterally, they are intercalated with medium- to coarse-grained sandstones bearing siltstone clasts, into which they may grade. Locally, they form basal lag deposits of channel sandstones. More frequently, they are shallow channel deposits

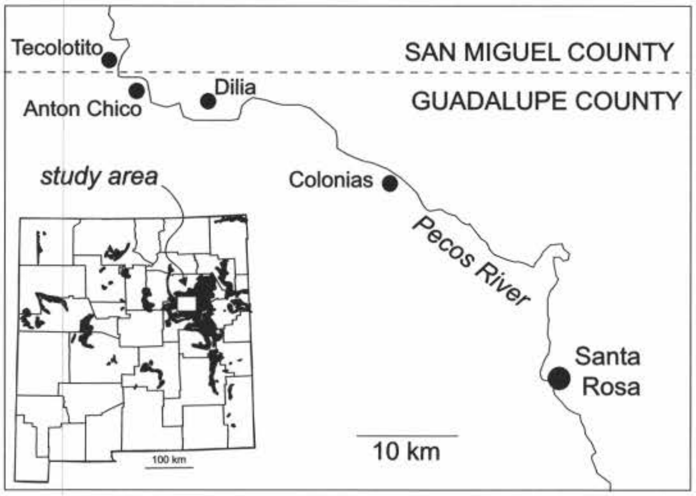


FIGURE 1. Distribution of Triassic strata in New Mexico (after Dane and Bachman, 1965), and detail of study area (from Tecolotito to Colonias) in San Miguel and Guadalupe Counties.

that may laterally intercalate with adjoining channel deposits, or they may overlie each other. The conglomerates usually, but not always, contain bones and vertebrate coprolites. In places, these components are accompanied by accumulations of black petrified (silicified) wood concentrated on single bedding planes.

Channelform sandstones dominate this facies. Overbank sediments represent only a small fraction of the section (around 10%), and conglomerates are confined to specific horizons. Many shallow channel deposits are filled with cross-bedded conglomerates or parallel-bedded overbank sediments. The general setting was that of a wide alluvial plain with branching, laterally shifting channels. Water levels changed according to long-term patterns, probably of seasonal origin, similar to megasequence 1 of the Pennsylvanian-Permian Cutler Formation in north-central New Mexico (Eberth and Miall, 1991).

The middle interval of the section is much more uniform than the lower. It consists of 1-4 m thick, fine- to coarse-grained sandstone layers. Bedforms are either indistinct, or large-scale cross-bedding that is partially trough-shaped and partially planar. In contrast to these wide-ranging channel-fills, silty overbank deposits are more localized, such as north of Tecolotito. Conglomerates are rare in this part of the section. At one site, conglomeratic lenses occur as lag deposits at the base of a channel sandstone. Only in the southern part of the study area are there abundant conglomeratic channel-fills. These may contain a few bones, but lack wood or coprolites (Fig. 2, level 6).

The upper part of the section is markedly thinner than the lower two parts and vertically more clearly subdivided than the middle part. There is a general trend from thin, cross-bedded fine-grained sandstones in the lower part to silty and fine-grained sandy overbank sediments in the upper part. Such fining-upward trends may have been produced by repeated cycles. Overbank deposits are horizontally laminated in their lower part, whereas in the upper part they lack clear stratification. Locally, especially in the southern part of the study area, the upper part of the Anton Chico Member may be rich in paleosols, as indicated by calcrete nodules and limonitic concretions. Conglomerates are laterally restricted, occurring in two different horizons. Bones were found in one place in interdigitating channel-fills (Fig. 2, level 7). In this part of the section, only one lacustrine deposit (near Tecolotito) was recognized, which is rich in vertebrates. Despite extensive prospecting, no other lacustrine horizons were found at this level. The predominance of overbank deposits suggests strong lateral restriction of channels between broad floodplains that formed interchannel flood basins. Sedimentation rates may have slowed down relative to accommodation as indicated by paleosols. The few available data match best with anastomosing and meandering river systems. These strata somewhat resemble fining-upward cycles (megasequence 2) of the Cutler Formation (Eberth and Miall, 1991), and similar cycles in the Molteno Formation of South Africa (Anderson et al., 1998).

## OCCURRENCE OF FOSSIL VERTEBRATES

Fossil vertebrates are confined to discrete stratigraphic levels in the Anton Chico Member. In addition to the two formerly known levels, we were able to recognize six more, which are, however, less rich in bones (Fig. 2).

Level 1—in the southern part of the study area, small, thin conglomerate lenses contain bone fragments. In the northern part of the study area, larger lenses are locally rich in vertebrate bones and contain few coprolites and occasional wood accumulations.

Level 2—mainly in the northern part of the study area, thin conglomerate lenses locally contain bones, coprolites and wood.

Level 3—in the southern part of the study area, a reworked soil horizon, consisting of coarse silt and filled with pedogenic concretions and occasional silty/sandy clasts, is rich in bone fragments. In the northern part of the study area, a complex system of thin, interfingering channel fills persists over long distances and is the main source of bone in conglomerates. Bones are much more frequent than coprolites. Some large, irregularly dispersed, wood accumulations are found, and invertebrate trace fossils are also present.

Level 4—only present in the middle part of the study area, several shallow channel fills and conglomerate lenses are locally accompanied by black, fine- to coarse-grained, carbon-rich sandstones. Coprolites are rare, bones even more so, but if present they are well preserved and complete; some wood is present.

Level 5—broad outcrops of conglomerate are generally barren of fossils but sometimes have a top consisting of thin, gray to light brown sandstone and siltstone. The latter yields numerous coprolites and amphibian bones and, slightly higher in this unit, wood. This level is also represented by another, stratigraphically unclear locality, where an erythrosuchid was found (Lucas et al., 1998).

Level 6—only known from the southern part of the study area, it consists of single channel fills, a few meters wide and with a maximum thickness of 1.3 m. These fills include conglomerates that rarely contain bone fragments.

Level 7—in the southern and middle part of the area, conglomerate lenses normally do not yield fossils. At one site the lenses are relatively thick (2 m), formed by a local channel complex that yields isolated bones and small archosauromorph teeth.

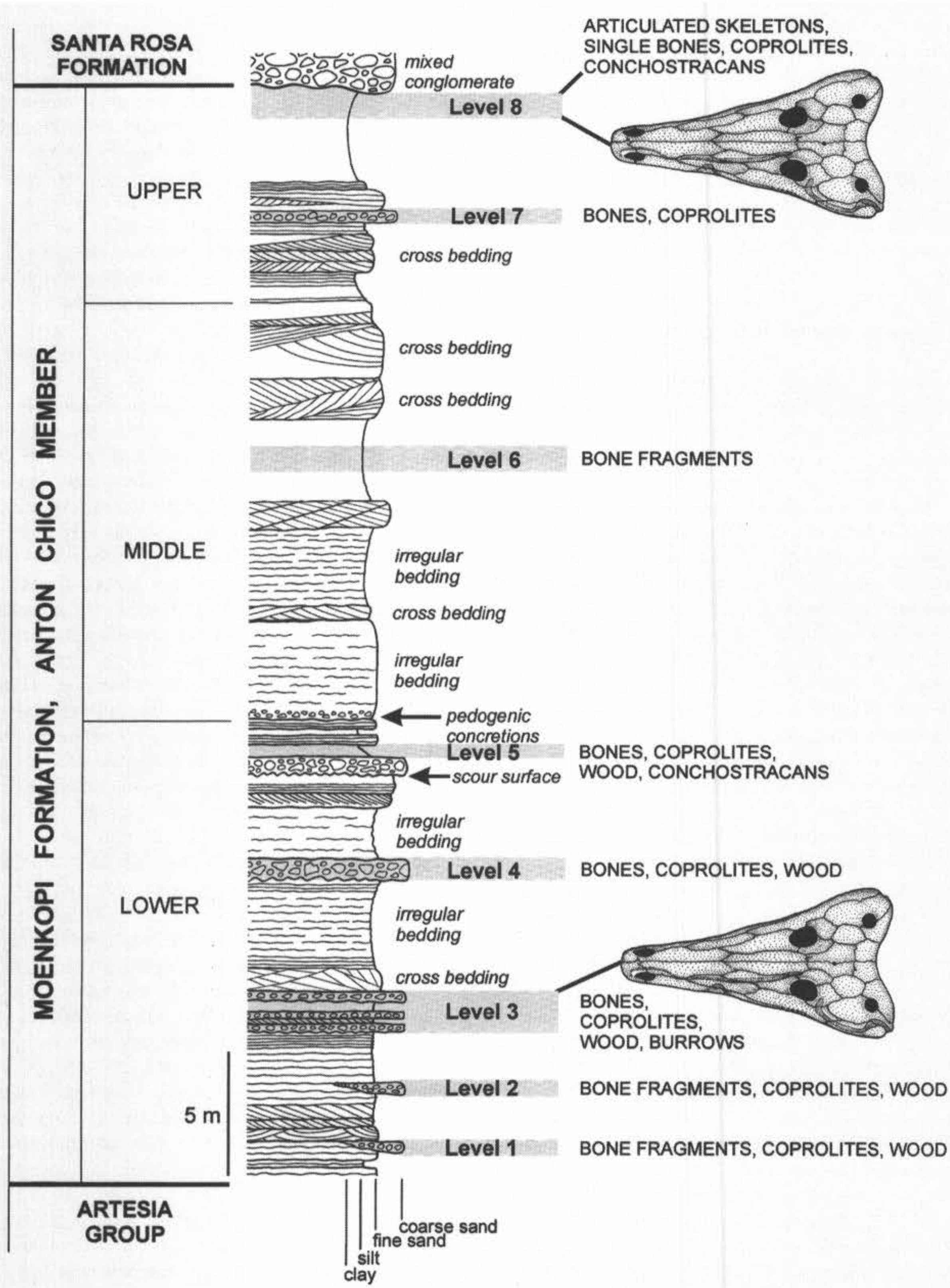


FIGURE 2. Stratigraphic section of the Anton Chico Member of the Moenkopi Formation in east-central New Mexico based on numerous field observations and a complete section measured on the Anton Chico Land Grant. The two skulls (*Eocyclotosaurus wellesi*) indicate the main vertebrate-bearing horizons.

Level 8—the top of the Anton Chico Member usually consists of gray to greenish siltstones and sandstones of varying thickness. These may contain thin conglomerate horizons, together with others rich in pedogenic pebbles. At one location, fine sandstones and coarse siltstones contain a rich deposit of coprolites, isolated bones and disarticulated skeletons.

## VERTEBRATE FOSSIL DEPOSITS

The different fossil levels can be grouped into two types of deposit--ephemeral water bodies (levels 5 and 8) and conglomeratic channel fills (levels 1-4 and 6-7).

### Ephemeral Water Bodies (Levels 5 and 8)

Short-lived ponds on floodplains were supplied with silty and fine sandy sediment during flooding phases. Compared with similar deposits in the Lower Permian (Sander 1987, 1989), the sediment in the Anton Chico Member is coarser, and evidence of a reducing environment (e.g., dark color, plant accumulation) is absent. This suggests only temporary water coverage and close proximity to a larger channel. Lithologically, there are no substantial differences from floodplain sediments. The frequency of aquatic tetrapods (*Eocyclotosaurus*), coprolites and conchostracans indicates quiet water conditions. Skeletons are likely to be disarticulated in warm climates and shallow water conditions (Wuttke, 1983; Elder and Smith, 1984). The sporadic occurrence of reptiles may be explained by reworking; this agrees with the much smaller average size of these elements compared to the amphibian remains, and with the predominance of teeth.

### Conglomeratic Channel Fills (Levels 1-4 and 6-7)

Vertebrate-bearing, channel-fill deposits may be derived either from abandoned channels containing water, or crevasse-splay channels (Behrensmeyer, 1988). Incised, thin, lenticular channel-fills are amalgamated to form complex channel systems, reaching a thickness of more than 2 m. Yet, the precise distribution and preservation of vertebrate remains in channel fills has not been studied so far. Locally, bones and bone fragments are concentrated in the tops of uppermost conglomeratic units. However, the vertebrate fossil content varies in different conglomeratic horizons. The abundance of coprolites also varies considerably; most appear to have been produced by temnospondyl amphibians. Also, the relative frequency of amphibian and reptile remains varies from site to site.

Typically, intraformational conglomerates in the Anton Chico Member bear vertebrate bones (Lucas and Morales, 1985; Lucas and Hunt, 1987). In most cases, these are interpreted as channel-lag deposits, in which current orientation and mechanical wear preserved only the most resistant bones within a certain size range. Examples have been documented by Olson and Barghusen (1962) in the Lower Permian of Oklahoma and Turner (1981) in the Upper Permian of South Africa. In addition, Behrensmeyer (1988) lists thin intraformational conglomerates embedded in fine-grained channel-fills as containing vertebrate Lagerstaetten; their formation is explained by weathering and limited reworking in abandoned channels during sporadic flooding events. However, in channel-fill deposits of the Anton Chico Member, conglomerates predominate, whereas fine-grained clastics are absent. An alternative possibility is that these conglomerates are parts of crevasse-splay channels. This would match the first phase in the displacement of main channels, in which shallow, unstable channels form (Smith et al., 1989). The sediments of these unstable channels have been reported to contain coarsening-upward sequences (Sander, 1989), whereas deeper channels should be characterized by a fining-upward trend (Eberth and Miall, 1991). The channel fills of the Anton Chico Member show only a faint fining-upward trend, if any.

Behrensmeyer (1988) gave a generalized synopsis of the preservation of vertebrates in fluvial deposits. She arrived at the following results:

1. In wide-ranging sheet sandstones, formed by main channels, vertebrate remains are sparse.
2. In fine-grained overbank deposits, vertebrates are also rare. There, however, they may occur in local accumulations or clusters, which sometimes include articulated specimens.
3. Rich deposits of vertebrates are found in channel lags of active channels. Bones are usually sorted and mostly disarticulated, with corroded edges, and generally very fragmentary.
4. Vertebrate accumulations frequently occur in abandoned channels above channel-lags. There are two principal categories: (i) sorted and fragmented bones in nodule and mudclast conglomerates, and (ii) better preserved, partially articulated material in fine-grained units of channel-fills.

Our present findings confirm Behrensmeyer's (1988) interpretation of vertebrate deposits; her types (1) and (2) are common in the Anton Chico Member, while (3) is rare and (4, i) is absent. Type (4, ii) is the most abundant type in our study area. This is not surprising, because complex channel-fills are dominated by conglomerates in the Anton Chico Member.

## MATERIAL AND VERTEBRATE FAUNA

The Moenkopi Formation was first recognized in New Mexico by S. G. Lucas in 1984 while collecting amphibian skull material of the genus *Eocyclotosaurus* (Lucas and Morales, 1985), known from the lower Anisian of central and western Europe (Welles and Cosgriff, 1965; Schoch and Milner, 2000). In Spring 1999, Lucas and Schoch collected material from various new localities that had been discovered by a private collector, A. Velasquez of Anton Chico. This material consisted of both isolated bones in conglomerates and articulated material in lake deposits. In Fall 2000, a field party of four people collected much more material in conglomerates, which is currently undergoing preparation. These finds form the basis of the present assessment of the vertebrate fauna of the Anton Chico Member. As the bulk of the vertebrate material is still to be prepared, we give only an incomplete, provisional list of taxa, which will probably be revised substantially.

### Fishes

Fish skeletons and isolated bones have not been found in the Anton Chico Member. There are, however, traces of fishes in coprolites, documenting the presence of actinopterygians. Level 3 contains anisopolar, spiral-shaped coprolites (*sensu* McAllister, 1996). This coprolite type is known from the Permo-Carboniferous of central Europe, where it is assigned to xenacanthid sharks (Boy, 1998). The Upper Triassic Chinle Group has also produced this type of coprolite, and they were also referred to xenacanthids by Hunt (1992). Both curled and uncurled coprolites in the Anton Chico Member contain thick, unsculptured scales of paleoniscoid actinopterygians. Together with these, we identified conchostracans and ostracods in coprolites. In the better-studied Moenkopi Formation deposits of Arizona, fishes are relatively rare--they occur in sediments rather than coprolites, and include sharks, dipnoans and paleoniscoids (McKee, 1954). The lack of fish remains in Anton Chico sediments may be explained by the following reasons:

1. Collection of vertebrates focused on larger bones rather than small fragments. Small and unspectacular fish elements and scales may have been overlooked, which is the most likely explanation.

2. Conglomerates are likely to lack delicate elements such as fish bones.

3. Fishes may have had difficulties in reaching the higher parts of river systems, which are obviously documented in the Anton Chico Member.

## Amphibians

Amphibians are the most abundant vertebrates in the Holbrook Member of the Moenkopi Formation in northern Arizona, where they reach a high morphological and taxonomic diversity (Welles, 1947; Welles and Cosgriff, 1965; Morales, 1987; Schoch, 2000). In the Anton Chico Member, they are abundant as specimens but taxonomically less diverse. At present, only capitosaur stereospondyls are known from the Anton Chico Member.

In conglomerates, amphibians are frequent, but not as dominant as in lake deposits. This may be explained by a longer transport of skeletons and single bones as documented by wear, or alternatively by greater distance from the actual habitats of stereospondyls. The presence and frequency of terrestrial forms such as archosaurs and prolacertiforms certainly demonstrates the proximity of a truly terrestrial ecosystem.

In both channel and lake deposits of the Anton Chico Member there is a wide range of amphibian sizes, from 100-400 mm skull length. In both types of deposits, a diversity of skeletal elements has been found. While the lake deposits contain semi-articulated specimens accumulated in great quantities, the conglomerates largely bear isolated bones, skull fragments or complete skulls in varying abundances. Sorting by transport certainly played a role, as the frequency of planar elements is clearly higher at some localities, whereas cylindrical vertebrae and limb fragments are more abundant at others.

### Heylerosauridae

A new species of *Eocyclotosaurus* is the most common amphibian in the Anton Chico Member. This species is closely related to *E. wellesi,* recently described from the Holbrook Member of Arizona (Schoch, 2000). It will be described and discussed in a separate, more detailed article. *Eocyclotosaurus* occurs in both river channel and lake deposits, and in the conglomerates it varies locally in frequency. In lake deposits it is abundant, forming nearly 90% of the assemblage. *Eocyclotosaurus* is characterized by a long and slender snout, small orbits set relatively laterally and a broad posterior skull with closed otic fenestrae. The snout of the Anton Chico morph is much more slender than in the European species of *Eocyclotosaurus*. Articulated finds show that the mandible is unusually low with a large meckelian window, and the axial skeleton includes crescent-shaped intercentra typical of small, primitive capitosauroids.

### Paracyclotosauridae

A second amphibian genus is known only from isolated and fragmentary skull and postcranial material. The distinctness of these finds is based on the morphology of the posterior skull table (especially the squamosal embayment) and the vertebral centra (intercentra). The cranial remains demonstrate this taxon to be an open-notched capitosauroid, similar to *Stanocephalosaurus* (Paracyclotosauridae) from the Holbrook Member of Arizona (Schoch and Milner, 2000). This is suggested by skull fragments of the otic region, the mandible and anterior palate, the latter being most diagnostic in capitosauroids. A second type of vertebral centrum is characterized by being more massive and a tendency to form a quasi-stereospondyl condition (formation of a closed disk), not by means of dorsal closure of the intercentral crescent, but by co-ossification of pleurocentra with each other and finally with the intercentrum. This is obviously a derived condition not found in other genera. Clearly, these intercentra are from a genus similar to *Stanocephalosaurus*, because they have the same relative position of the parapophysis (Schoch, 1999).

### Unidentified large capitosauroids

Very large bones in the conglomerates suggest the presence of much larger stereospondyls. Among these finds are skull, mandible and girdle fragments suggesting a morphology different from that of the aforementioned genera. At this preliminary stage it is impossible to clarify the assignment of these large amphibians; they may either represent a third taxon, or merely large specimens of one or both other taxa. *Eocyclotosaurus wellesi* from Arizona is known to have grown much larger than its European relatives (Schoch, 2000).

## Reptiles

The Anton Chico Member is unique among all Moenkopi members in having numerous reptile fossils. They clearly exceed the frequency of reptiles in the Holbrook Member, and at many sites (in intraformational conglomerates), reptile remains outnumber those of amphibians. The reptiles also are the largest vertebrate remains in the Anton Chico Member, reaching limb bone dimensions of more than half a meter.

The conglomerates have yielded numerous vertebral centra, limb bones and girdle elements of a range of reptiles differing in size and morphology. Skull fragments, teeth and neural arches are generally much rarer and more fragmentary. This largely isolated material is only diagnostic at the family level. The significance of this material is nevertheless remarkable: it is the only Lower/ Middle Triassic archosaur material gathered in great quantity, and for the first time a North American terrestrial fauna may be compared to that of other continents.

### Erythrosuchid

In 1997, a partially articulated skeleton of a very large archosaur was found in a lake deposit near Dilia, east of Anton Chico (Lucas et al., 1998). Revisting the site yielded more material, especially vertebrae and osteoderms, which reach the dimensions of the South African genus *Erythrosuchus*. The locality was on the slope of a shallow gully where bones had been weathering out of a light greenish-gray shale rich in plant debris, conchostracans (estherians) and vertebrate coprolites. We interpret this as an especially quiet-water phase of a small lake that must have persisted over a long time period. The erythrosuchid bones had obviously been under water, as the mandibular alveoli contain bivalves in life position.

### Medium-sized primitive archosaur

The conglomerates are rich in vertebrae (centra) and appendicular elements of medium-sized archosaurs comparable to *Ticinosuchus ferox* in size and gross morphology. Humeri, femora, scapulae, ilia and fragmentary cranial elements suggest that they represent a somewhat more primitive archosaur than *Ticinosuchus*, but clearly more derived than *Erythrosuchus* and *Shansisuchus*. They form more than 70% of the reptile remains found in the conglomerates. The ilia, in particular, have a rather plesiomorphic morphology similar to the Russian genus *Vjushkovia*.

### Advanced rauisuchians

A few isolated postcranial remains are distinct from the bulk of the archosaur material, and document the presence of a second taxon. The most definitive evidence is ischia that are remarkably similar to poposaurids and, especially, chatterjeeids (Long and Murry, 1995). The presence of such advanced archosaurs would be highly significant for the understanding of the radiation of early archosaurs, but at present the remains are too fragmentary to permit definite conclusions.

### Prolacertiforms

Elongated neck vertebrae and thoracic vertebral centra suggest the presence of plesiomorphic, short-necked prolacertiforms. Only vertebrae have so far been identified, and they are from animals about the size of *Protorosaurus*. These finds are much rarer than the archosaur vertebrae and limb elements, but it is unclear which of the smallest bones, such as tail vertebrae and small limb elements, might belong to this taxon.

### Reptile teeth

Teeth are extraordinarily rare, except in the floodplain pond deposits. In an amphibian-dominated pond deposit, several small (1-2 cm long) archosaur teeth were found. They are short and moderately wide, resembling phytosaur teeth. In most channel conglomerates, only jaw fragments have yielded teeth so far, and they are from rauisuchians. A small conglomerate locally rich in unusually small bones has also produced some archosaur teeth and one jaw fragment with a dentition resembling procolophonids that needs further investigation.

Reptile bones are abundant in the conglomerates, especially in Level 3. Locally they are more abundant than amphibians. The most common finds are vertebral centra and complete tail vertebrae of small archosaurs. Girdle elements are rarer and fragmentary, and limb bones are mostly present as smaller fragments of robust proximal and distal ends. Delicate skull fragments, neural arches and ribs are much more rare.

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At Sierrita de la Cruz, north of Amarillo, Texas, badlands are developed in the Tecovas (slopes) and Trujillo (sandstone cap) formations of the Chinle Group. These Upper Triassic strata are riverine floodplain and channel deposits that yield one of the world's most important fossil records of Late Triassic terrestrial life.