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# HISTORY OF MESOZOIC LAKES OF NORTHERN NEW MEXICO

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## ABSTRACT

A series of lakes, both large and small, existed in New Mexico in late Chinle time (Triassic) and in Entrada, Todilto, and early Morrison time (Late Jurassic). Especially in the early part of this history, several small lakes, rather than one large lake, were present. Size, shape, and location changed from time to time, in such a way that regional tilting must have been important. That the regional slope changed during this time interval, is also indicated by variations in patterns of stream-type cross-bedding.

The maximum dimension of the largest lake was approximately 500 km, from northwest to southeast. Some of the water bodies, particularly in late Chinle time, were only ponds. During late Entrada time, former sand dunes projected as islands above the lake surface, to be planed off ultimately as the water level rose.

The main lake was salty for part of its history (late Todilto time), but in general appears to have been fresh. Fossils from limestone beds (early Todilto time) either have freshwater affinities or are indeterminate. There is no evidence for marine deposits within the lake basin.

The extensive dune field of early Entrada time represented an interruption in the lake history, as did other eolian deposits (either not deposited in, or perhaps subsequently eroded from, the Ghost Ranch area). Prior to the development of this dune field, and also after the termination of the early Morrison lake, the area was marked by either low rolling wooded hills, or stream courses and alluvium, or both.

The history presented here has been obtained from cross-bedding, ripple marks of three varieties (eolian, current, wave), mud-cracks, algal mounds, ostracods, fish, tree trunks and other plant debris, coal and various other evidences. Modern analogs have provided the methodology for estimating fetch and wave height.

## INTRODUCTION

A sequence of shallow-lake deposits is preserved in New Mexico and adjacent states, in strata of Triassic and Jurassic age (Tanner, 1965, 1968, 1970, 1971a). The formations of interest are:

Morrison (Late Jurassic)
Todlito (Late Jurassic)
Entrada (Late Jurassic)
(Non-deposition? Early Jurassic)
Chinle (Triassic).

The Morrison is easily divisible into two units, an upper multicolored clay and silt bed containing thin porcellanite units and well-developed sand-and-gravel-filled channels, and a lower unit which is in large part sandstone. This lower unit has been given various names in different places, but is referred to here simply as "lower Morrison sandstone." This lower sandstone unit commonly contains, or is below, the silica-bleb bed which characterizes the lower Morrison in many states (McKee and others, 1956).

The Todilto, a limestone-and-gypsum sequence, is widely recognized as having been deposited in a large body of shallow water. Whether that water was fresh, continental saline, or marine, has been the subject of debate. The absence of known marine fossils or of intertonguing with other marine beds suggests that the marine interpretation is the weakest of the three. The presence of considerable gypsum indicates high salinity for part of its history. The large, well-developed algal mounds along the western and southern margins, the non-marine ostracod fossils, and the numerous examples of a fossil salmonid fish indicate that the limestone member was deposited in a freshwater lake (Tanner, 1970). The work by Stapor (1972) on the petrology of the Todilto Formation likewise minimizes the possibility of a marine origin. When the Todilto is considered in its proper stratigraphic position, between lake deposits below and lake deposits above, it clearly appears to have had a lake origin.

The Entrada Sandstone is partly eolian and partly lacustrine. The eolian origin is demonstrated by the widespread combination of spectacular wind-type cross-bedding and numerous eolian ripple marks (Tanner, 1966). The latter, although present by the thousands, are so fragile (as is typical of eolian ripple marks in general) that they can be seen only on bedding planes on freshly-fallen talus blocks, and then only when the sun is at the right position; a casual search, spread over a few days, is not good enough to locate these common but elusive features. The lacustrine origin is shown by clay partings, water-laid cross-bedding of the torrential type, mud-cracks and wave-type limited-fetch ripple marks. Where the Entrada is thick (roughly 90 meters) it is typically all or essentially all eolian; where it is thinner (around 70 meters) the lower two-thirds are commonly eolian and the upper third is lacustrine. This observation leads to the suggestion that during the first part of Entrada history, the area was covered by a dune field, whereas during the latter part, a few larger dunes rose as sand hills above the lake surface.

The Chinle and Entrada formations are separated by an unconformity which represents approximately half of Jurassic time. Farther west, this interval is occupied by the Carmel, Navajo, Kayenta, and Wingate formations and their equivalents. In the Ghost Ranch area, the Early Jurassic was a time of non-deposition rather than of pronounced erosion. It is possible that the lowest portion of the Entrada represents some part of this interval.

Because a history of lakes, marshes and other lowlands has been adduced from beds both below and above the Wingate-to-Carmel gap, it is thought that roughly the same conditions prevailed during that time span, but that the general subsid-

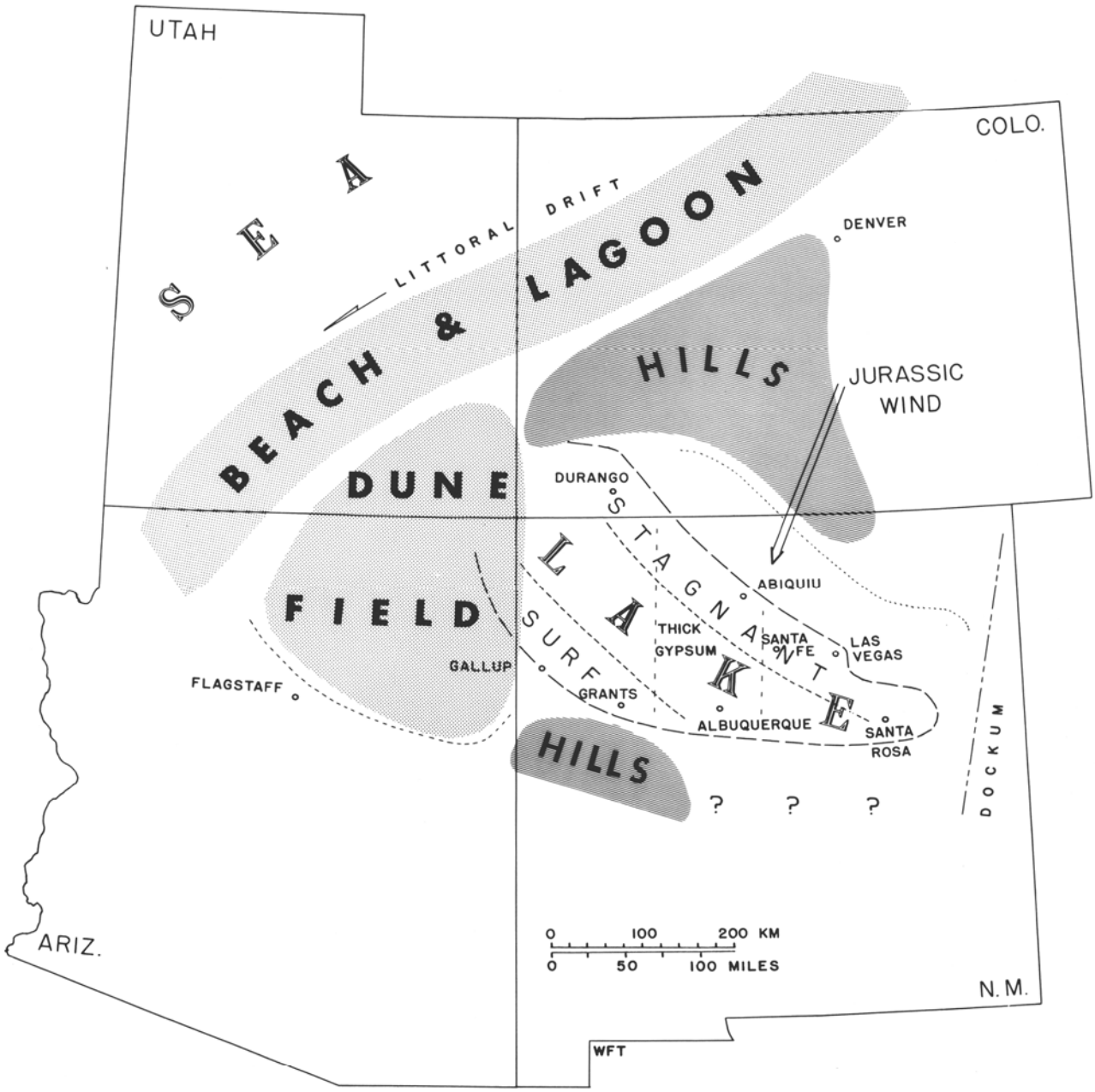


*Figure 1. Paleogeography for latest Entrada, Todilto, and early Morrison time, in the four state area of New Mexico, Arizona, Utah and Colorado. Hill areas, dune field, beach-and-lagoon strip and sea are highly generalized. The prevailing wind is shown blowing from the north-northeast, but this includes a strong northerly component from Triassic time; there is also evidence for sea breezes blowing northwest-to-southeast across the beach and lagoon strip. The maximum Todilto lake is outlined by a dashed line; the northeastern part is shown as "stagnant" and the southwestern part as "surf," and a central strip of "thick gypsum," which was deposited in the latter part of Todilto time, is also shown. The dotted line northeast of Abiquiu is the probable maximum northeasterly extent of the lake in latest Entrada time. Known Permian mountain blocks (between Santa Fe and Las Vegas, for example) have been omitted, even though they probably produced irregularities in the lake shore. During early Entrada time, dune sands covered most of the lake bed; the dune field shown on the map was developed largely in post-Chinle, pre-Entrada time, as well as in Entrada time. Details of the lake shore, the edge of the stagnant belt, and the edge of the surf zone, are not shown, even where known. It is not certain that the Todilto marsh or shallow lake, in the vicinity of Santa Rosa, was continuous with the main body of the lake, although it may have been. There is no evidence for an opening between the northwestern end of the lake and the sea beyond, but on the other hand little is known of the lake shore (the lake itself, through most of its history, was not saline). The lake shown here is the largest in a set, or series, of lakes which existed in this area, changing size, shape and location through much of Triassic and Jurassic time, as a result of gentle warping of the basin floor.*

ence, which farther west was making room for accumulation of a thick sedimentary section, did not operate in the Ghost Ranch area. In any case, there is no known evidence to suggest that the lake-marsh-lowland history of Late Triassic and Late Jurassic time was modified in any significant way during Early Jurassic time.

Much of the section that is missing in the Ghost Ranch area is, farther west, spectacularly eolian. In other words, the dune field, which was important in the Ghost Ranch area in Entrada time, actually began its history much earlier in the Jurassic in Arizona and Utah.

The Chinle Formation consists of an upper silt-and-clay unit, containing local lenses of sandstone, and a lower unit which includes several thick, varied and conglomeratic members, each having a member name. The lower conglomeratic members (exposed, for example, in Blackie's Meadow and east of Blackie's cabin on Ghost Ranch) were deposited by flowing streams under continental conditions. The small sandstone lenses in the upper unit are, in good part, pond and small lake deposits. The presence of petrified tree trunk fragments, limb prints, and coal pebbles, as well as other evidence, points to continental deposition.

Beds below the Chinle, of Permian age, are continental. Cretaceous beds above the Morrison are coastal marine (beach, lagoonal, coastal marsh, shallow near-shore, etc.). The sequence which can be reconstructed, from Permian into Cretaceous time, is: continental stream, continental including lakes, continental dune field, continental including lakes, one large lake (youngest Entrada, Todilto and lower Morrison sandstone), continental stream, coastal, and marine. Mild tectonic deformation, however, prevented streams from flowing in the same direction throughout this history (Tanner, 1971b); instead, the regional slope direction varied markedly from time to time. It is presumed that gentle warping was also responsible for repeated changes in the sizes, shapes, and locations of the various lakes, both large and small.

## RIPPLEMARKS

The key to the lake history of the Triassic-Jurassic sequence of strata is the ripple mark. Three basic ripple mark types can be found in the area: eolian, current, and wave. The eolian ripple marks (referred to above) are wide, so flat as to be invisible when sunlight is falling directly on the bedding plane, and very common in the Entrada. Because these ripple marks can be seen only on the bedding planes of freshly-fallen blocks, orientations and hence wind directions cannot be obtained. However, eolian cross-bedding is easy to measure (Tanner, 1965); the wind, in Entrada time, blew from the northeast or east-northeast (modern coordinates).

The current ripple marks are highly asymmetrical, short-crested and moderately flat (large ripple indices), and have only poor parallelism, all typical features of this category (Tanner, 1967). They are rare or absent in the lacustrine beds, but occur locally elsewhere in the continental part of the section.

The wave ripple marks are symmetrical or nearly so, tall (low values for the ripple index), straight and parallel except for minor and local deviations (Tanner, 1967). They can be divided into two sub-classes, on the basis of ripple mark spacing. Those having crests less than 5 cm apart are positive evidence for highly restricted fetch: that is, small lakes. Those having crests 5 cm or more apart could have formed under either marine or lacustrine conditions. Because there is no evidence for a marine intrusion into the area in Triassic and Jurassic time, all of the straight and parallel ripple marks are interpreted as having a lacustrine wave origin.

The spacing of ripple marks is a function of particle size (which can be measured), water depth (which in some instances can be inferred with fairly good accuracy), and wave parameters. The latter depend on water depth, fetch, wind speed, and wind duration. Wind speed and wind duration cannot be recovered, unless one is willing to make the assumption of "average windiness"; this assumption is a safe one when large numbers of ripple mark fields can be studied (Tanner, 1970, 1971a). More than 200 ripple mark fields were examined in the Ghost Ranch area, and hence "average conditions" can be assumed. Because many of the sand lenses can be observed in full, and because many of the bedding features (such as mud-cracks and flat-topped ripple marks) require specific shallow water depths, the depth and fetch are known in many instances, and the depth in many more. In the latter case, the combination of ripple mark spacing, grain size and water depth is enough to permit one to estimate fairly closely the fetch distance (Tanner, 1970, 1971a).

Stormy or highly windy conditions are excluded; they produce ripple marks larger than the average. Calm conditions are likewise excluded; they do not produce ripple marks.

The fetch obtained from grain size and ripple mark data is the upwind distance to the nearest shore or other barrier (such as a reef or shoal that is awash), and does not provide any information as to the down-wind distance. Therefore the width of the lake cannot be less than the indicated fetch, but it might be much greater. For this reason, the Triassic-Jurassic sequence of strata has been examined on all sides of the large basin which contain the largest lake.

From the lower Morrison sandstone in the Ghost Ranch area, one learns, for example, that the average ripple mark spacing (200 ripple mark fields) is 3.39 cm; the fetch was 3 to 7 kilometers. Presuming that the prevailing winds, which formed the eolian cross-bedding, also drove the "average condition" waves (although these two agencies were not operating at precisely the same moment in time), one deduces that the fetch is to be measured toward the northeast or east-northeast. Ripple mark orientation is not the best method to obtain fetch direction, for two reasons: (a) the crests provide two opposite directions, and (b) crest orientation also reflects tiny variations in bottom slope.

From lower Morrison sandstones near U.S. Highway 66, on the south side of the lake, the average ripple mark spacing was 11 cm, indicating a fetch of close to 200 km, again toward the northeast. These two localities, however, are almost exactly 200 km apart, hence the lower Morrison lake must have had a width of 200 km, from about Grants to Ghost Ranch. This is also the maximum width, in this direction, with an error of less than 10%, because Grants and Gallup are located on, or very close to, the shoreline.

The lake in late Entrada time had a different size and different shape. The fetch near Ghost Ranch was close to 100 km, again assumed to be in the upwind direction (average spacing, 9.5 cm). How far the upper Entrada lake extended to the southwest and south is not known, for no wave-type ripple marks were found in the Entrada and its equivalent (part of the Zuni sandstone) near U.S. Highway 66.

Ripple marks from the Triassic lenses on Ghost Ranch were asymmetric but straight and parallel, a characteristic of ripple marks formed by waves moving into shoaling water; the common text-book assertion that asymmetric ripple marks necessarily indicate current flow is not correct. The average spacing was 6.2 cm, indicating a fetch of 20 to 30 km. The asymmetry indicates that the fetch is to be taken to the north, but bottom effects cannot be ruled out, and hence this direction is not certain. The width toward the south is not known.

From three different sets of ripple mark fields, the fetch to the north or northeast has been shown to be 20 to 30 km (Upper Triassic), about 100 km (upper Entrada; Jurassic), and 3 to 7 km (lower Morrison; Jurassic). Furthermore, variability within these sets also indicates changes, from time to time, in the fetch. And the presence of sand hills standing as islands in the Entrada lake indicates that shoreline geometry must have been changing in detail (for sand transport reasons) as well as in general (for tectonic reasons).

Water depths in these lakes were typically very shallow, 1 meter or less, around the coasts, and probably commonly less than three meters, but locally as much as 40 m. Wave heights along the southern and southwestern shores of the lower Morrison lake probably averaged close to 15 cm, which is much higher than the "Big Bend" coast of Florida, where "zero energy" conditions prevail (Gulf of Mexico wave heights average only about 1 cm). In the late Entrada lake, wave heights were, on the average, about 10 cm. In the late Chinle lakes, from indications on Ghost Ranch, wave heights were about 5 cm, although this figure would vary from one lake to another, in view of the fact that height depends on fetch.

Storm waves may have been two to three times the average height.

## CIRCULATION

Greater variability can be demonstrated for the largest lake than the smaller ones, as is to be expected. During early Todilto time, the southwestern margin of the lake (downwind) was characterized by active surf, with average breaker heights near 15 cm and rough-weather breakers probably close to 50 cm. Large, well-developed algal mounds were present. The limestone which accumulated at that place and time is pale-gray-to-wh ite.

The northeastern margin of the lake (up-wind) was characterized by near-stagnant conditions, as indicated by the dark color and fetid odor of the Todilto limestone. Broken fragments of plant matter probably indicate marsh conditions, or vegetation growing in the shallow near-shore part of the lake. All of the known Todilto fish fossils have been collected from this part of the formation. Breakers were very small to nonexistant, either because the fetch was strictly limited (only a few kilometers at the most), or because the sub-aqueous meadow absorbed the wave energy (or both).

During Entrada and early Morrison time, there was no limestone deposition, and clean sandy bottom was the rule on all sides of the lake, even along the upwind margin where fetch was minimum. Under modern sea-shore conditions, submarine meadow develops extensively in very shallow water where average breaker heights are less than about 4 or 5 cm. If this criterion is used to distinguish between the stagnant or near-stagnant environment along the up-wind edge of the Todilto lake, and the good circulation along the up-wind edge of the Entrada and early Morrison lake, then a secondary wind field can be adduced. Evidence for such a wind field has been found in the eolian cross-bedding of the region (Tanner, 1965), but the large distances involved make it unlikely that this was a sea-breeze effect.

It is also possible that a change in water chemistry, associated with the deposition of first limestone and then gypsum, accounts for the extensive cover of aquatic plants along the upwind shore in Todilto time, and that reduced circulation was a result of that plant growth rather than of wind and wave effects.

In late Entrada time, when sand hills protruded above the lake surface in the Ghost Ranch area (much like the Pleistocene dunes which make up the Gulf of Mexico islands in the vicinity of Cedar Key, Florida, today, where average wave heights are only 2 to 5 cm), circulation patterns must have been complicated. Detailed studies of micro-cross-bedding in the upper Entrada, on and near Ghost Ranch, could resolve this question, at least in part, but no such work has been done.

Wave and current differences across the smaller lakes and ponds must have been unimportant, and circulation was certainly of no significance in the various marshes. The influence of the astronomical tide would have been negligible.

## CLIMATE

The lakes were situated southeast (modern coordinates) of a marine coast which lay across Utah and Colorado (Tanner, 1965). The main lake basin was at least partly surrounded by hills which furnished some of the pebbles found in the Triassic-Jurassic strata. The northwest-shore of the lake was 100 to 200 km from ocean water farther northwest, and the southeastern edge, likewise defined only poorly, was perhaps 600 to 700 km away from that marine arm.

During Late Triassic and Early Jurassic time, the study area was located about 27° north (present location is about 36° north); however, compass bearings would not have been markedly different from what they are now (McElhinny, 1973, p. 203). Barring wind-field distortions due to mountains, the study area would have been within the northeast trade wind belt (winds from the north-northeast). The arm of the sea across northern Colorado, Wyoming, and Idaho would have been the source of most moisture, except for minor precipitation brought on sea breezes from the northwest. All of this arises from an extrapolation backward into time of modern air circulation patterns, and gives results compatible with deductions from field observations (such as eolian cross-bedding).

The existence of a large lake demonstrates the presence of an ample water supply; the streams and plant fossils of the Upper Triassic Chinle Formation likewise require at least moderate rainfall. The potential evaportion at 27° latitude is roughly 200 cm/year (Gerasimov, 1964). In order to maintain the maximum lake (about $10^5$ $km^2$) against evaporation, precipitation over the lake and runoff from the adjacent plains and hills (about 4 x $10^5$ $km^2$) would have to have been more than about 50 cm/year. This requires precipitation over the land of more than about 150 cm/year (about 60 inches/year) (Linsley and others, 1949, p. 93, 225).

The 9-degree difference in latitude indicates a warmer climate, by about 3° C (5.4° F), barring landmass effects, about which we know very little. Parts of the Mexican coastal plain along the Gulf of Mexico, today, might be reasonable analogs; perhaps the strip from Veracruz to Tabasco.

The altitude of the adjacent hills is, of course, unknown, and hence no allowance can be made for increased precipitation which might have fed larger streams having a greater discharge. The absence of large deltas indicates that lower hills and generally more rainfall provide a better interpretation than high mountains, especially to the north, where a tall mountain range would have placed the lake area effectively within a rain shadow, thus guaranteeing aridity or semi-aridity.

The reason for the appearance and then disappearance of the Jurassic dune field is now known. Several hypotheses are available, including the possibility that the hills to the north were rejuvenated sharply, thus providing a wind barrier. The absence of conglomerate beds in the proper stratigraphic positions makes this suggestion questionable. (The tectonic deformation of the area, referred to in earlier paragraphs, is thought to have been gentle warping, rather than orogeny.) Other hypotheses likewise cannot be evaluated adequately at the present time.

## CONCLUSION

One or more lakes existed in the Ghost Ranch area, and other parts of New Mexico and adjacent states, during late Chinle, Entrada, Todilto and early Morrison time. The largest lake was developed in early Todilto and early Morrison time, and perhaps during the later part of Entrada time. Even this largest lake, however, was not fixed in size or shape. At its maximum it extended westward to the Chuska Mountains (on the Arizona line), southward to about U.S. Highway 66 from near Gallup, New Mexico, to east of Santa Rosa, New Mexico, and eastward to about Las Vegas, New Mexico, as well as north-westward into southwestern Colorado and southeastern Utah. The width, parallel with the wind (northeast-southwest) was about 200 km. In the longest direction (northwest to southeast), the lake was probably 500 km wide at the time of its greatest development.

Three unusual episodes affected lake history: (1) production of a limestone deposit during early Todilto time, when the influx of elastic material was minimal; (2) deposition of gypsum during late Todilto time, when the lake waters were salty; and (3) mixing of eolian and lacustrine environments during Entrada time, (and perhaps in Early Jurassic time also), when wind activity was particularly important. When there were several smaller lakes, as in late Chinle time, the area appears to have been a wooded lowland or hill region, with streams, marshes and ponds, as well as one or more lakes.

The return from the large lake of early Morrison time, to the alluvial plain of late Morrison time, appears to have been relatively sudden.

## NOTE

Procedures for treating field data, in order to draw paleogeographic inferences, have been described in two earlier papers (Tanner, 1970, 1971a). The first of these papers contains typographical errors in the appendix, where the notation "in" should be corrected to read "ln" (that is, natural log). Eq. (1) in the 1970 paper is Eq. (14) in the 1971 paper; and Eq. (2) in the earlier paper is Eq. (18) in the later paper.

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