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TOROWEAP FORMATION

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INTRODUCTION

The Permian Toroweap Formation in the Grand Canyon region is one of the most intriguing, if not the most readily noticed, formation when viewed from the commonly visited overlooks in Grand Canyon National Park (Fig. 11.1). The Toroweap occupies the generally tree-covered interval between the overlying Kaibab Formation, which forms the rim of the Grand Canyon, and the underlying Coconino Sandstone, which forms a prominent light gray cliff that is visible from great distances. What the Toroweap Formation lacks in scenic splendor in the eastern Grand Canyon, it compensates for in its geologic diversity. The Toroweap exhibits some of the most striking lateral facies changes in the Grand Canyon sequence. McKee (1938) was the first to recognize the lateral facies changes in the Toroweap in his classic monograph on the Kaibab and Toroweap Formations. More recently, geologists have conducted stratigraphic and facies analyses of the Toroweap in the context of modern sedimentologic concepts. This work has permitted a reevaluation of the depositional environments and has resulted in a fairly complete paleogeographic reconstruction of the Toroweap Formation.

NOMENCLATURE AND DISTRIBUTION

The Toroweap Formation in Arizona, which covers an area of approximately 25,000 square miles (65,000 km^2), is best exposed in the Grand Canyon region and in outcrops along the Mogollon Rim. It pinches out in the subsurface to the east of the Grand Canyon, but extends northward in the subsurface into southern Utah, westward into eastern Nevada, and southward in the subsurface to the outcrop belt along the Mogollon Rim. Beyond this point, erosion has removed evidence of the formation.

In 1938, McKee described and named the Toroweap Formation, which he separated from the overlying Kaibab Formation (Fig. 11.2). The type locality for the Toroweap is in Brady Canyon, an eastern side canyon to Tuweep (Toroweap) Valley. McKee recognized three informal members: an upper evaporite and redbed interval—the alpha member; a middle limestone unit—the beta member; and a lower sandstone and evaporite interval, which he referred to as the gamma member. Sorauf (1962) applied geographic names to McKee's informal members (Fig. 11.3). He named the alpha member the Woods Ranch Member; the beta the Brady Canyon Member; and the gamma the Seligman Member. Sorauf and Billingsley (1991) have proposed formally that these member names be accepted.

In addition to dividing the Toroweap Formation into members, McKee (1938) divided the formation into three lateral phases: the western phase, where the three members are recognizable; the transition phase, which consists of irregular-bedded sandstone; and the eastern phase, which consists of cross-bedded sandstone (Fig. 11.2). The limits of the western phase are determined by the extent of the Brady Canyon Member. To the east and southeast of the pinchout of this member, the two other members (the Seligman and Woods Ranch members) cannot be distinguished. The western phase is well-developed in the Grand

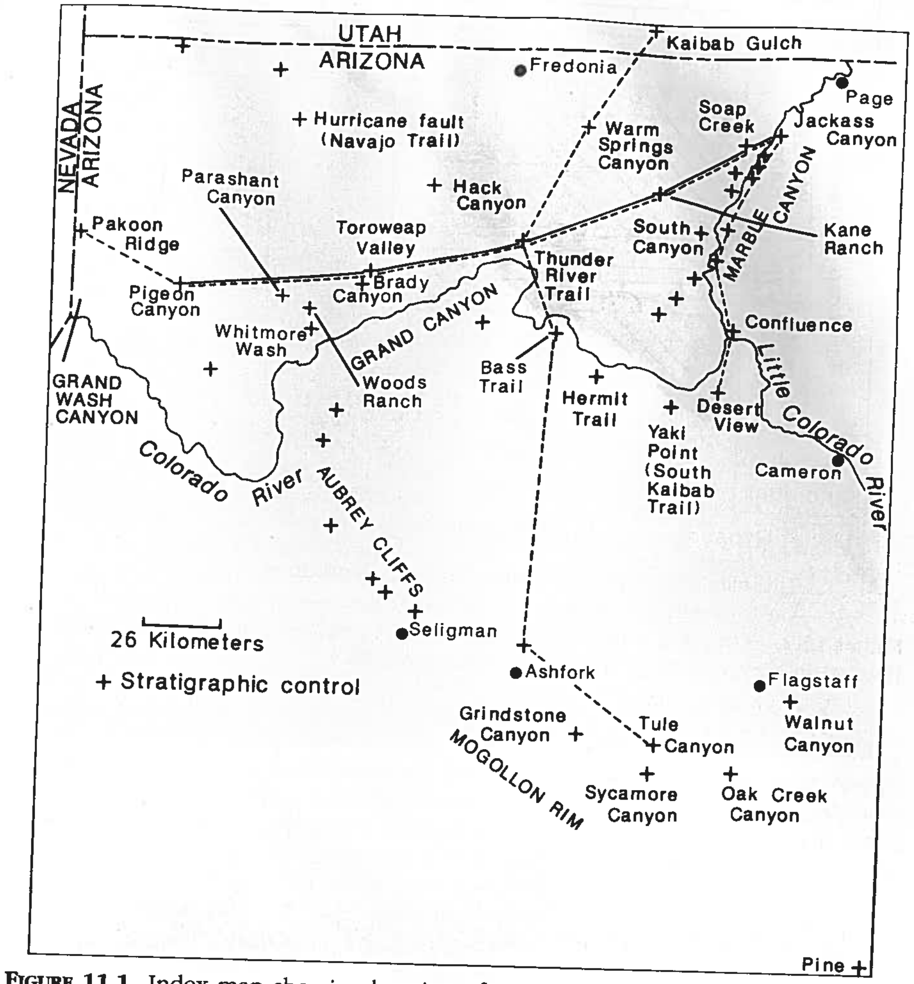

FIGURE 11.1. Index map showing location of measured sections used in this study. Dashed lines indicate lines of section used to construct panel diagram shown in Fig. 11.3. Solid lines indicate line of section used to construct the correlation diagram shown in Fig. 11.3. Solid lines indicate line of section used to construct the correlation diagram shown in Fig. 11.12.

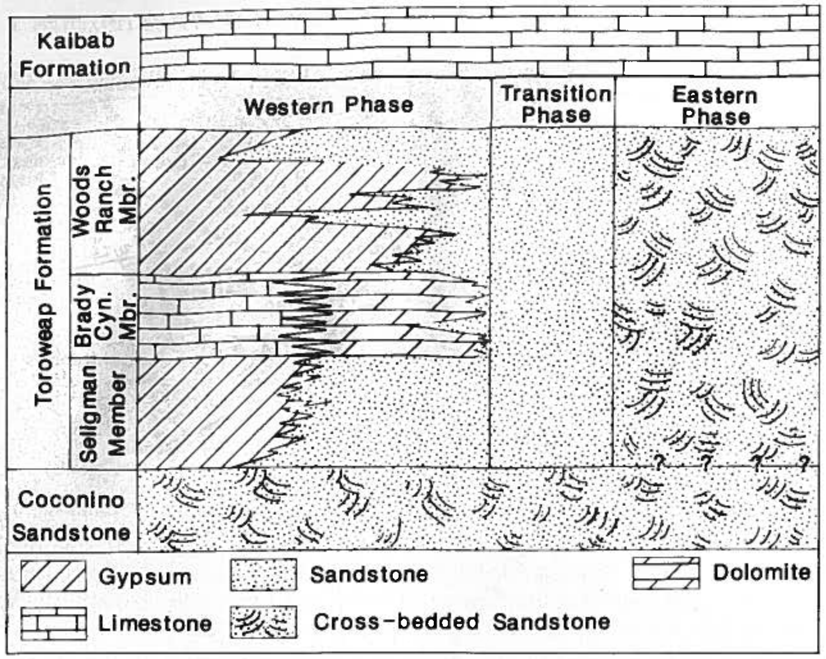

FIGURE 11.2. Schematic diagram showing members and lateral phases of the Toroweap Formation. (From Rawson and Turner-Peterson 1979.)

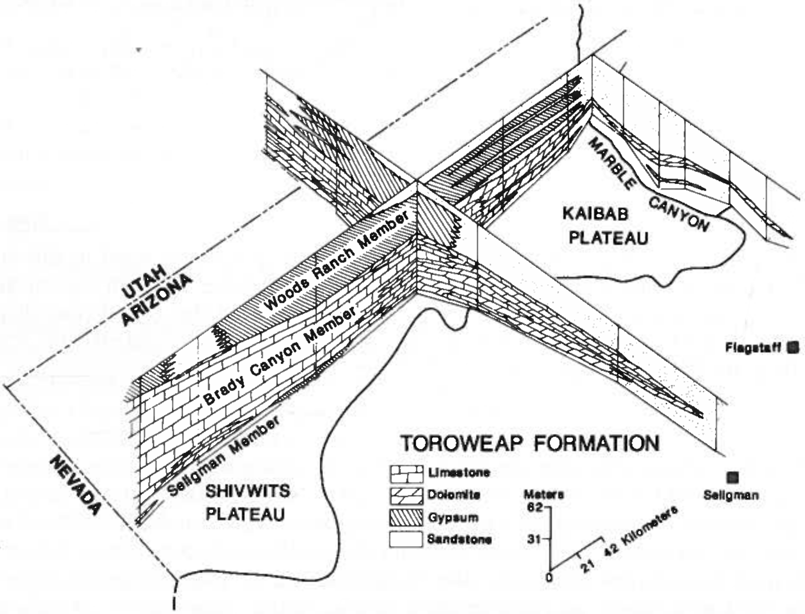

FIGURE 11.3. Panel diagram constructed chiefly in the western phase of the Toroweap Formation, along lines of sections shown in Figure 11.1. Note thinning of Brady Canyon Member to the east and southeast, as well as an increase in dolomite in that member. Evaporites in Woods Ranch and Seligman members are confined largely to the area north of the Grand Canyon. (From Rawson and Turner-Peterson 1974.)

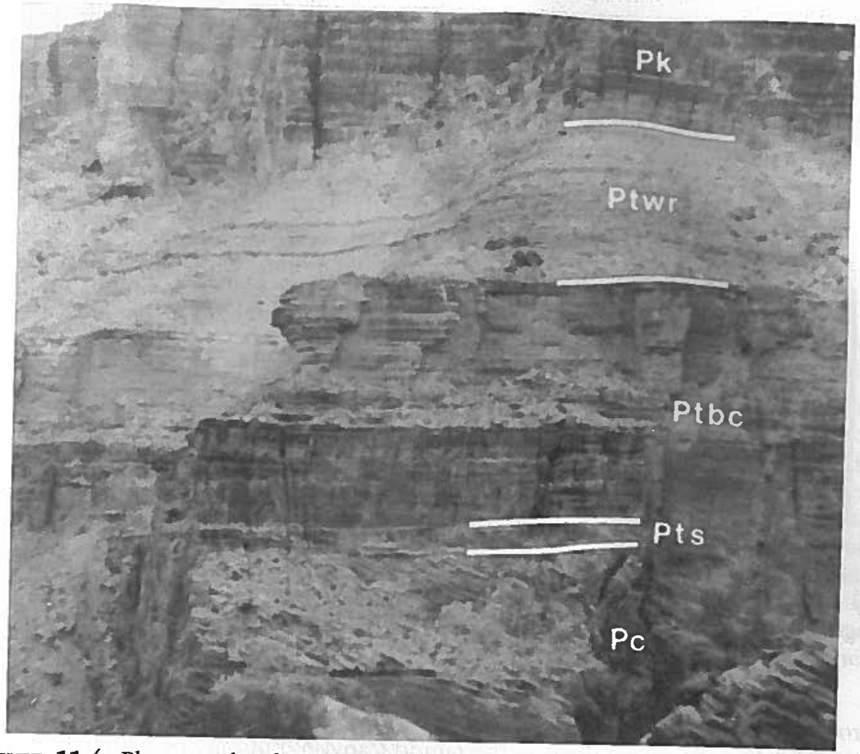

FIGURE 11.4. Photograph of Toroweap Formation in South Canyon, near Marble Canyon (see Fig. 11.1 for location). Presence of all three members is characteristic of the western phase. Pk, Kaibab Formation. Members of the Toroweap are: Ptwr, Woods Ranch Member (slope-forming unit in this region because of gypsum beds); Ptbc, Brady Canyon Member (cliff-forming carbonate units); Pts, Seligman Member (thin sandstone interval). Pc, Coconino Sandstone.

Canyon region (Fig. 11.4). The transition phase of the Toroweap is particularly well-developed in the area of Sycamore Canyon. To the south and east of this area, the sandstones are more extensively cross-bedded. The Toroweap Formation in Oak Creek and Walnut canyons typifies McKee's eastern phase and is characterized by cross-bedded sandstone (Fig. 11.5).

LITHOLOGY AND STRATIGRAPHY

Stratigraphy

Geologists can identify all three members in the Grand Canyon region (Figs. 11.2 and 11.3). The lower boundary of the Toroweap Formation is at the base of the Seligman Member. It is the first non-cross-bedded or evaporite-bearing unit above the cross-bedded Coconino Sandstone. The boundary is conformable in most locations but is not distinct in the area of Marble Canyon, where cross-bedded units of the Coconino Sandstone intertongue with the lowermost beds of the Seligman Member. The first appearance of a thick carbonate unit above the non-

Figure 11.5. Photograph of Oak Creek Canyon showing cross-bedded sandstone typical of the eastern phase of the Toroweap Formation. Line of vegetation, indicated by arrow, marks the boundary between the Toroweap Formation and the underlying Coconino Sandstone, a unit that also contains cross-bedded sandstone. Pk, Kaibab Formation; Pt, Toroweap Formation; Pc, Coconino Sandstone.

cross-bedded sandstone defines the upper contact of the Seligman Member. It is less than 45 feet (15 m) thick in the Grand Canyon, but may be as much as 450 feet (152 m) thick in the North Muddy Mountains in Nevada (Bissell 1969).

The Brady Canyon Member forms the massive cliff of carbonate above the relatively thin Seligman Member in the Grand Canyon region (Fig. 11.4.) Limestone predominates to the west, whereas dolomite is abundant to the east (Figs. 11.2 and 11.3). The Brady Canyon Member has its greatest development in the western Grand Canyon, where it is up to 280 feet (93 m) thick. It thins uniformly in an easterly direction to a depositional edge just east of Marble Canyon. An aphanitic dolomite unit with prominent desiccation cracks marks the upper contact here.

The Woods Ranch Member typically extends from the top of the aphanitic dolomite that forms the uppermost unit of the Brady Canyon Member to the base of the cliff-forming limestone of the overlying Kaibab Formation. Repetitive intervals of evaporate, limestone, and sandstone form a distinctive slope in most of the Grand Canyon region. Where the Woods Ranch Member lacks evaporate, it usually forms cliffs. The Woods Ranch Member shows no consistent thickening or thinning trends throughout most of the study area. Geologists have measured a maximum thickness of about 180 feet (60 m).

Along the Mogollon Rim of central Arizona, the three members of the Toroweap disappear because of lateral facies changes. That fact, plus the presence of an additional member at the base of the Kaibab Formation, requires that different criteria be used to define the lower and upper contacts of the Toroweap Formation.

In the Sycamore Canyon area, the upper contact of the Toroweap is difficult to identify because the sandstone beds of the Fossil Mountain Member (the basal unit of the Kaibab Formation in this area) resemble the sandstone beds of the Toroweap Formation.

In the Oak Creek Canyon area, cross-bedded sandstone characterizes the entire Toroweap Formation, making it difficult to differentiate this formation from the underlying Coconino Sandstone. However, a truncation surface marked by vegetation in surface exposures separates beds contemporaneous with the Toroweap Formation from the underlying Coconino Sandstone (Fig. 11.5).

Lithofacies

Evaporite Lithofacies Interbeds of evaporate, thin-bedded carbonate, and fine-grained sandstone characterize a significant part of the Woods Ranch Member (and to a lesser degree, the Seligman Member). The lithofacies is restricted in both members to the area north of the Grand Canyon (Figs. 11.6 and 11.7). The evaporate beds, which most often are gypsum, frequently contain laminae of limestone and dolomite (Figs. 11.8a and b) several millimeters thick. The evaporate in these laminated intervals usually is about one centimeter thick. Evaporite beds occur in sequences characterized by a basal carbonate unit up to 1.5 feet (0.5 m) thick, gypsum beds up to 3 feet (1 m) thick, and sandstone beds that generally are 1.5 feet (0.5 m) thick. The carbonate beds, which typically are limestone rather than dolomite, are thinly laminated and vuggy (Fig. 11.8c). Gypsum or anhydrite nodules fill the vugs in places. This suggests that all of the vugs originally may have been filled with evaporate minerals. Frequently, the sandstone beds are poorly cemented, and it is difficult to discern sedimentary

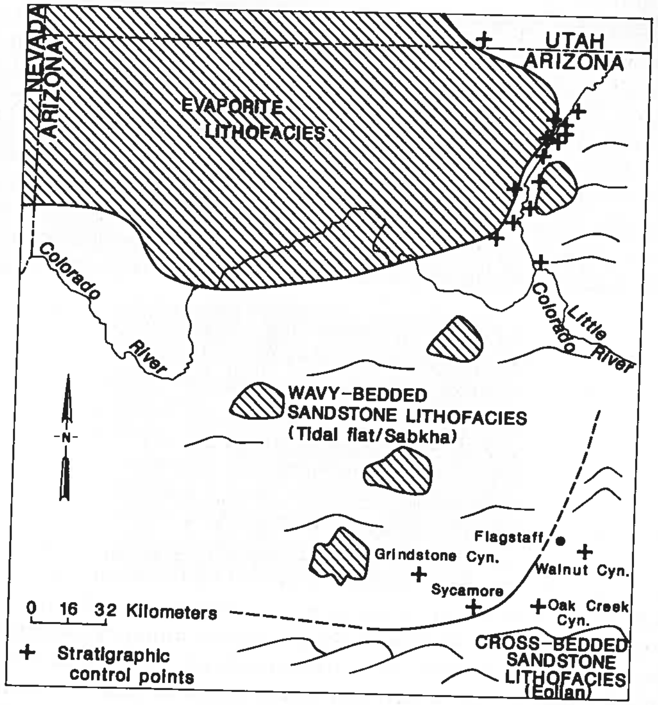

Figure 11.6. Map showing distribution of lithofacies in Seligman Member and equivalent strata in the Toroweap Formation. Map is based on the most abundant lithofacies present at each locality. (Modified from Rawson and Turner-Peterson 1974.)

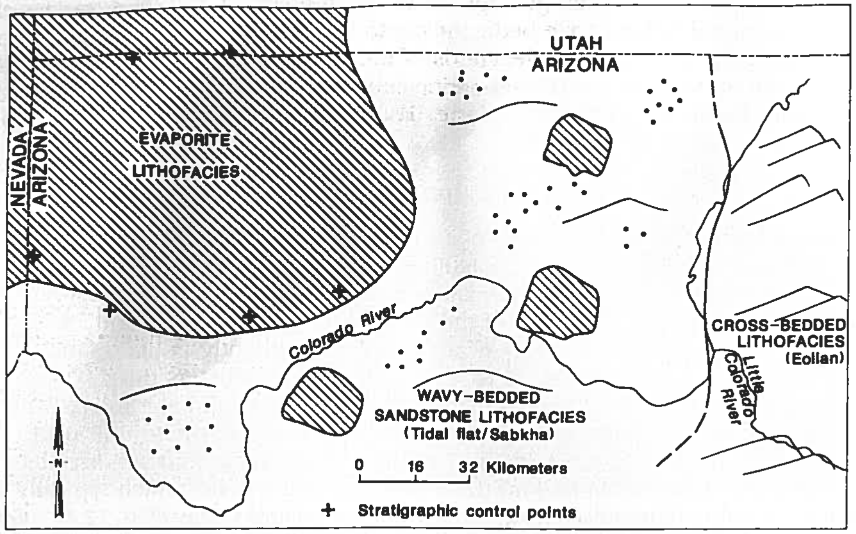

FIGURE 11.7. Map showing distribution of lithofacies in Seligman Member and equivalent strata in the Toroweap Formation. Map is based on the most abundant lithofacies present at each locality. (Modified from Rawson and Turner-Peterson 1974.)

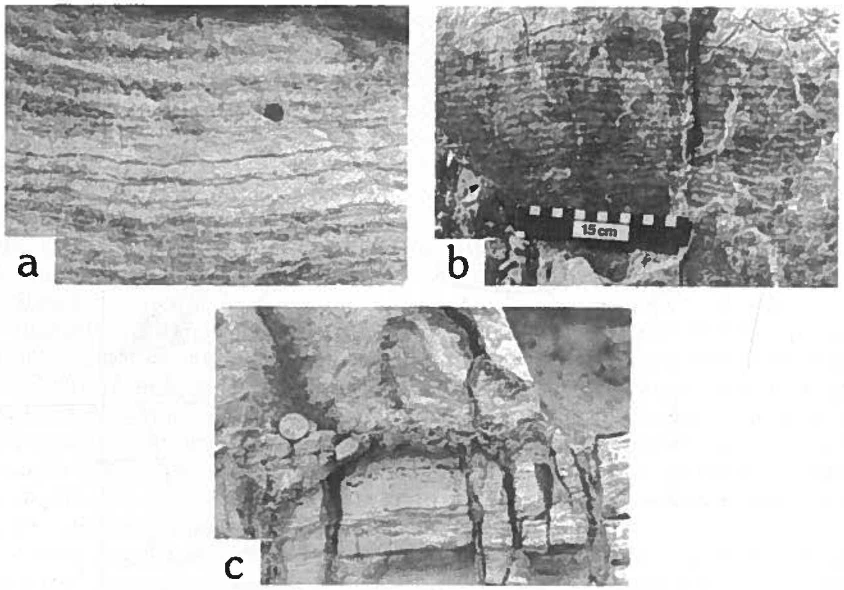

FIGURE 11.8. Features observed in the evaporite lithofacies of the Toroweap Formation. Photographs are from the Woods Ranch Member along the Thunder River Trail, Grand Canyon. (a) Gypsum bed (white bands) with thin laminae of limestone (gray), with penny for scale; (b) Laminated bed that contains alternations, on the scale of a few millimeters, of gypsum (white) and limestone (gray); (c) Thin-bedded limestone bed with vugs near the top (below and to the right of the quarter), overlain by bed of gypsum. Locally, similar vugs are filled with evaporite minerals, suggesting that these vugs originally contained evaporites.

structures. Locally, however, geologists can identify cross-bedding. With the exception of one thin limestone bed near the top of the Woods Ranch Member (a unit that contains abundant pelecypods of the genus *Schizodus*), this lithofacies is unfossiliferous. The *Schizodus*-bearing limestone bed, which contains ooids locally, has been named informally the "Hurricane Cliffs tongue" of the Woods Ranch Member (Altany 1979).

The evaporite lithofacies probably represents deposition in a shallow, subaqueous, shelf environment in which warm restricted-marine waters were evaporated, promoting the precipitation of evaporite minerals. Originally, geologists thought that this lithofacies represented sabkha deposition (Turner 1974; Rawson and Turner-Peterson 1974, 1979, 1980); we now know that laminated evaporites indicate precipitation in standing water rather than formation by displacive growth within sabkha sediments (Schreiber 1986). The thinly laminated evaporate and carbonate (Fig. 11.8b) is similar to the anhydrite–carbonate couplets in the laminated sulfate facies in subaqueous evaporates of the Castile Formation of the Delaware Basin of southeastern New Mexico and western Texas. Some carbonate units in the evaporate lithofacies of the Toroweap Formation contain desiccation cracks, which indicate local subaerial exposure and thus shallow, rather than deep, water deposition. Most likely, this lithofacies was part of a shallow shelf sequence. The carbonate units also lack fossils, which suggests that conditions in the restricted-marine waters were not conducive to marine life. Vertical repetition of certain lithologies—a basal carbonate bed, middle evaporate bed, and upper sandstone unit—suggests that cyclic sedimentation characterized deposition of this lithofacies. Thin carbonate laminae within the evaporate beds reflect periodic freshening of the waters that were depositing the evaporite. We do not know if this freshening occurred on a seasonal basis.

Siliciclastic Lithofacies

Irregular-Bedded Sandstone Fine- to medium-grained sandstone and siltstone characterize the intervals of the Woods Ranch and Seligman members that are laterally adjacent and equivalent to the evaporite lithofacies. This lithofacies dominates in areas just to the east and southeast of the evaporate lithofacies of the Woods Ranch and Seligman members (Fig. 11.6 and 11.7). In addition, this lithofacies predominates in the entire Toroweap Formation and beyond the depositional edge of the Brady Canyon Member (Fig. 11.2), typifying the transition facies of McKee (1938). Carbonate and evaporate beds are rare in this lithofacies, in contrast to their abundance in the evaporate lithofacies. Typical sedimentary structures include wavy lamination (Fig. 11.9a), flaser lamination (a discontinuous form of wavy lamination), lenticular lamination, and fluid-escape structures. Minor cross-bedded, fine-grained sandstone units with sets of inversely graded laminae occur in this lithofacies. Locally, these units exhibit high-index ripples whose axes trend directly down the cross-bedding laminae. Geologists also have noted wave and adhesion ripples (Fig. 11.9b) as well as brecciated (and rare) thin carbonate beds (Fig. 11.9c).

Intraformational brecciation is a common feature in this lithofacies, particularly in Marble and Sycamore canyons, within the transition facies defined by McKee (1938). The breccia most often consists of blocks of cross-bedded eolian sandstone within a matrix of flaser (or lenticular) laminated sandstone. The cross-bedded blocks typically show evidence of having collapsed downward (Fig. 11.9d). In the Sycamore Canyon area, laterally extensive beds of brecciated sandstone are interbedded with cross-bedded sandstone.

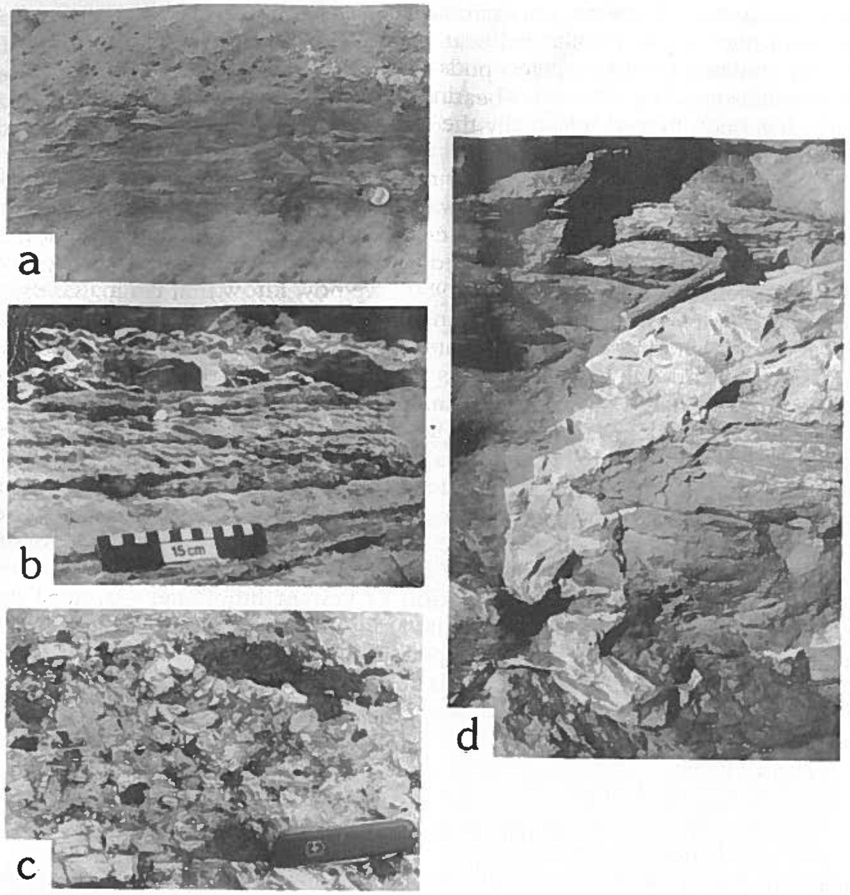

Figure 11.9. Features observed in the wavy-bedded sandstone lithofacies of the Toroweap Formation. Photographs a–c are from the Woods Ranch Member along the South Kaibab Trail, near Yaki Point in the Grand Canyon. (a) Wavy and lenticular bedding, with penny for scale. (b) Adhesion ripples at the top of a cross-bedded sandstone. (c) Brecciated carbonate beds, with knife for scale. (d) Cross-bedded, light-colored sandstone bed (immediately below hammer) collapsed into underlying units. This may have been caused by removal of evaporites by dissolution. From the Woods Ranch Member in Jackass Canyon, near Marble Canyon, Arizona.

Most geologists interpret the irregular-bedded sandstone lithofacies as tidal-flat deposits. Flaser bedding, wavy bedding, and lenticular bedding are characteristic of intertidal environments (Reineck and Wunderlich 1968), whereas brecciated carbonate units similar to those in the Toroweap Formation generally occur in supratidal zones of tidal-flat complexes (Shinn 1983). The brecciation found in carbonate beds probably is related to the dolomitization of limestone beds in a supratidal setting. This dolomitization results in shrinkage that is caused by a loss of volume. The abundance of fluid-escape structures is consistent with a tidal flat environment. Cross-bedded units that exhibit inverse, graded bedding and high-index ripples on the slipface almost certainly are eolian dune deposits.

Although dune deposits are not abundant in this lithofacies, they do indicate the occasional migration of eolian sediments across the tidal-flat surface. Limited paleocurrent data from the eolian sandstones in this lithofacies show a southerly transport direction, which is consistent with the paleowind directions for the Permian in the Colorado Plateau region (Peterson 1988).

One possible interpretation for areas in the transition phase that contain abundant intraformational sandstone breccias is a supratidal or sabkha environment. This interpretation relies in part on the regional facies interpretation that Rawson and Turner-Peterson (1979) have proposed for the Toroweap Formation. Most of the brecciation occurs in the southeastern part of the study area, in the part of the transition facies that contains the largest number of eolian sandstone units. This is particularly true in the Sycamore Canyon area, where laterally extensive, brecciated sandstone units interbed with cross-bedded eolian sandstone. In the overall facies distribution, brecciated units occur landward of the intertidal deposits and are intercalated with eolian sandstones. Fryberger et al. (1983) have suggested a supratidal or siliciclastic-sabkha environment to explain similar laterally extensive, brecciated units. It is possible that the evaporite formed by displacive growth within a siliciclastic sabkha. Subsequent removal of this evaporate by the movement of relatively fresh groundwater through the sandstones would have caused collapse and brecciation within the sabkha units.

Cross-Bedded Sandstone The irregular-bedded and brecciated sandstone units of the transition phase of the Toroweap Formation grade laterally, in a southeasterly direction, into cross-bedded sandstone of the eastern phase of the Toroweap (Fig. 11.2). The eastern phase is characterized by fine- to medium-grained, cross-bedded sandstone that is indistinguishable from sandstone in the underlying Coconino Sandstone (Fig. 11.5). Most frequently, the cross-beds are wedge and tabular planar (Fig. 11.10a), with some trough-shaped sets. Average set thickness is about 6 feet (2 m), and the average dip direction is S11°W, with a consistency ratio of 0.90 (Rawson and Turner-Peterson 1979). The sets of cross-bedded sandstone contain thick avalanche or sand flow toes as much as 0.5 inches (5 cm) thick (Fig. 11.10b) and inversely graded laminae (Fig. 11.10c). Slumping and deformational features are not uncommon in this lithofacies (Fig. 11.10d).

We base an eolian interpretation for this lithofacies on the presence of diagnostic eolian characteristics, such as large-scale cross-bedding, avalanche (sand flow toe) deposits, and inversely graded ripple laminae. The deformational structures shown in Fig. 11.10d are similar to those studied in modern environments and seem to develop exclusively in dunes that are wet or that have been wetted (McKee and Bigarella 1972). The eastern-phase Toroweap Formation may have been deposited in a coastal dune environment. An eolian interpretation also is consistent with the southeasterly transport direction for the cross-bedded sandstone lithofacies; this direction is the same as that determined for the eolian rocks of the underlying Coconino Sandstone. It also is consistent with paleowind directions during the Permian in the Colorado Plateau area (Peterson 1988).

Carbonate Lithofacies Geologists have identified several carbonate lithofacies within the Brady Canyon Member of the Toroweap Formation. Rawson and Turner-Peterson first described these lithofacies in 1974.

Skeletal Packstone Skeletal material in the grain-supported carbonate in this lithofacies consists of disarticulated crinoid columnals; bryozoans; brachiopods; ostracods; gastropods; endothyrids; echinoid and brachiopod spines; and trilo-

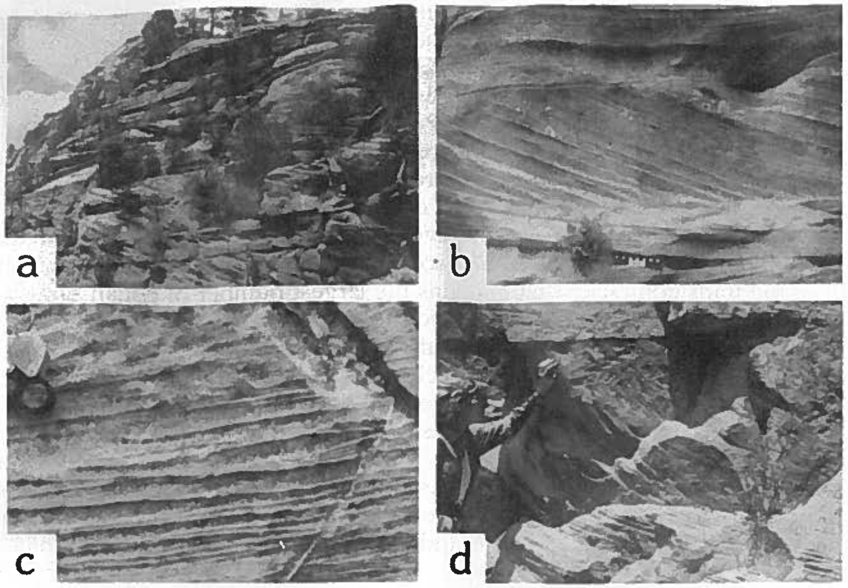

Figure 11.10. Features observed in the cross-bedded sandstone (eastern phase) of the Toroweap Formation. (a) Section composed almost entirely of a tabular- and wedge-shaped, cross-bedded sandstone, Oak Creek Canyon, Arizona. (b) Avalanche (sand flow) toes observed in cross-bedded sandstone, Oak Creek Canyon, Arizona. (c) Inversely graded laminae in cross-bedded sandstone, Sycamore Canyon, Arizona. Note preservation of foreset laminations in middle part of photograph. 10× hand lens for scale. (d) Deformational structures in cross-bedded sandstone, Oak Creek Canyon, Arizona. These structures seem to develop exclusively in eolian dunes that are wet.

bite fragments. The matrix is micrite, which is common to all of the carbonate lithofacies. Although only a few grainstones are present, we can see rare quartz grains in thin section. The quartz, which is fine-silt-size, increases in abundance from west to east. This lithofacies is common in the western part of the Grand Canyon region.

Pelletal Wackestone This lithofacies consists of carbonate units that contain elliptical-to-spherical pellets ranging from 0.004 to 0.008 inches (0.1 to 0.2 mm) in diameter. No true ooids occur, except in the "Hurricane Cliffs tongue" of the Woods Ranch Member. The pelletal wackestone facies commonly is altered to a dolomicrite, which geologists include in this facies when they can recognize the original texture. Dolomitized pelletal wackestone is prevalent in the eastern part of the study area and also occurs in some western sections, particularly near the top of the Brady Canyon Member.

Sandy Dolomite A sandy dolomitic lithofacies is abundant in the Marble Canyon area. It also occurs near both the base and the top of the Brady Canyon Member in the western part of the study area. The dolomite is silt-size, with abundant fine-to-coarse, sand-size quartz grains.

Aphanitic Lime Mudstone and Dolomite Aphanitic lime mudstone and dolomite commonly occur at the base and top of the westernmost exposures of the Brady Canyon Member in the study area. This lithofacies probably is present to the east as well, but quartz grains mask the texture. The carbonate is aphanitic (0.004 mm in diameter), and the dense rock that it forms breaks with a conchoidal fracture. To date, geologists have not found fossils or fossil fragments in this unit. Desiccation cracks, common in this lithofacies, are readily observed at the top of the Brady Canyon Member in most localities (Fig. 11.11).

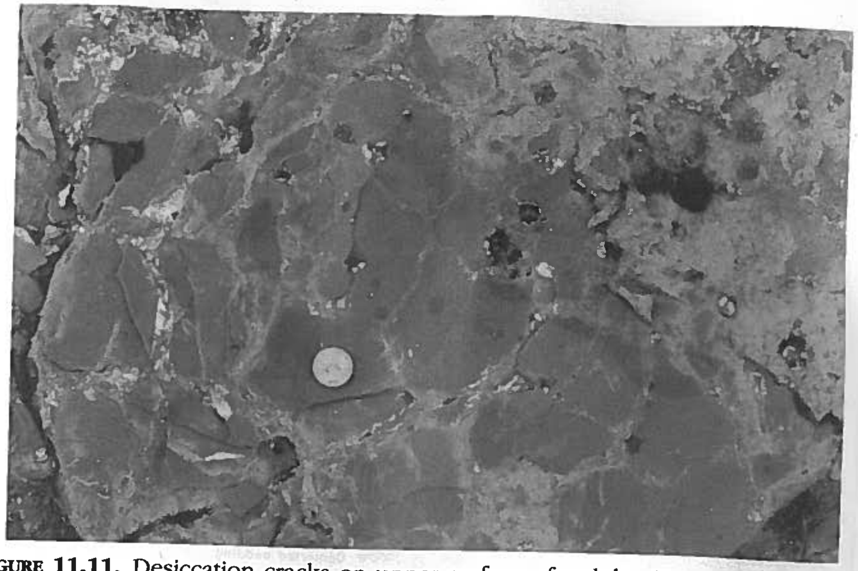

Figure 11.11. Desiccation cracks on upper surface of a dolomitic mudstone at the top of the Brady Canyon Member. Desiccation cracks such as these are abundant at this same interval across northern Arizona and probably indicate widespread withdrawal of the sea at the end of deposition of the Brady Canyon member. Quarter for scale.

Distribution and Interpretation of Carbonate Lithofacies

During the formation of the Brady Canyon Member, carbonates with an open-marine fauna were deposited to the west, whereas carbonates with a restricted-marine fauna were deposited to the east (Fig. 11.12). This reflects an incursion of the sea from the west. The mud-supported texture that characterizes all lithofacies of the Brady Canyon Member indicates that these sediments were laid down in quiet-water conditions and that there was no significant reworking. The fauna and textural types are consistent with shallow, quiet-water conditions on a carbonate shelf. Distribution of lithofacies in the Brady Canyon Member changed through time. Figure 11.13 shows a representative distribution of lithofacies at one particular time (T-2 in Figure 11.12). Gradation from open-marine fauna in limestone beds in the west to restricted-marine fauna in dolomitic mudstone in the east, as shown in Figure 11.13, is characteristic of the Brady Canyon Member. Of particular interest is the persistence of a dolomitic mudstone at the top of the member (R-3 in Fig. 11.12). This represents a westward progradation of a lithofacies deposited in the most restricted of marine conditions. Also noteworthy is the frequent occurrence of desiccation cracks on the upper surface of this

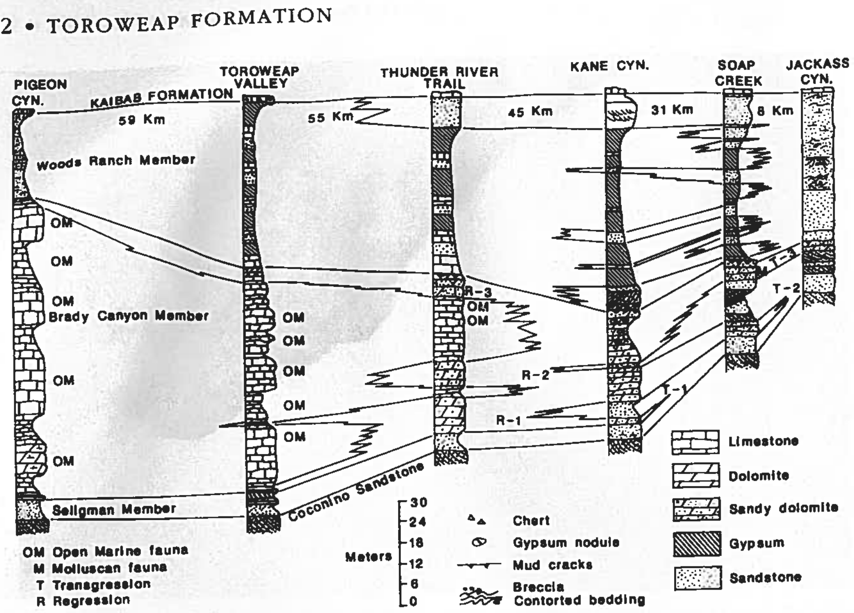

FIGURE 11.12. West-to-east correlation diagram of the Toroweap Formation, northern Arizona (see Fig. 11.1 for locations). Evaporites in the Seligman Member represent the first incursion of the sea following deposition of the underlying eolian Coconino Sandstone. In the Brady Canyon Member, open-marine fauna predominate to the west, and restricted-marine fauna predominate to the east. Several transgressions and regressions are apparent within the Brady Canyon Member. Regression R-3 may represent progradation westward in response to a slowing down of a relative sea level rise, and the top of the Brady Canyon Member (marked with desiccation cracks) may represent a relative drop in sea level. The evaporite lithofacies of the Woods Ranch Member is thought to reflect another relative sea level rise. (Modified slightly from Rawson and Turner-Peterson 1974.)

dolomite unit, indicating widespread subaerial exposure at the end of deposition of the Brady Canyon Member.

Current models of dolomite formation do not explain the greater abundance of dolomite in the eastern part of the Brady Canyon Member. The idea of reflux dolomitization implies a syndepositional process, where dolomitization occurs in response to the movement of hypersaline brines from a lagoonal environment into adjacent or underlying carbonate sediments (Adams and Rhodes 1960). Although evaporites are present in the Woods Ranch Member of the Toroweap Formation, the distribution of these evaporites does not coincide entirely with the distribution of dolomite in the underlying Brady Canyon Member (Fig. 11.3). An alternative model, the "Dorag" dolomitization model (Badiozamani 1973), implies the replacement of earlier formed limestone intervals in a "mixing zone" of seawater and fresh water.

Although some of the carbonates in the Brady Canyon may have been dolomitized in this way (e.g., some pelletal wackestone beds), replacement textures are not abundant in the carbonate beds. As Hardie (1987) points out, we do not understand the process of dolomitization very well. Distribution of dolomite in the Toroweap Formation, as in many ancient examples, clearly is greater in the more restricted-marine lithofacies. This association suggests that restricted circulation and great evaporation promote dolomite precipitation, but we do not know the mechanism by which it occurs.

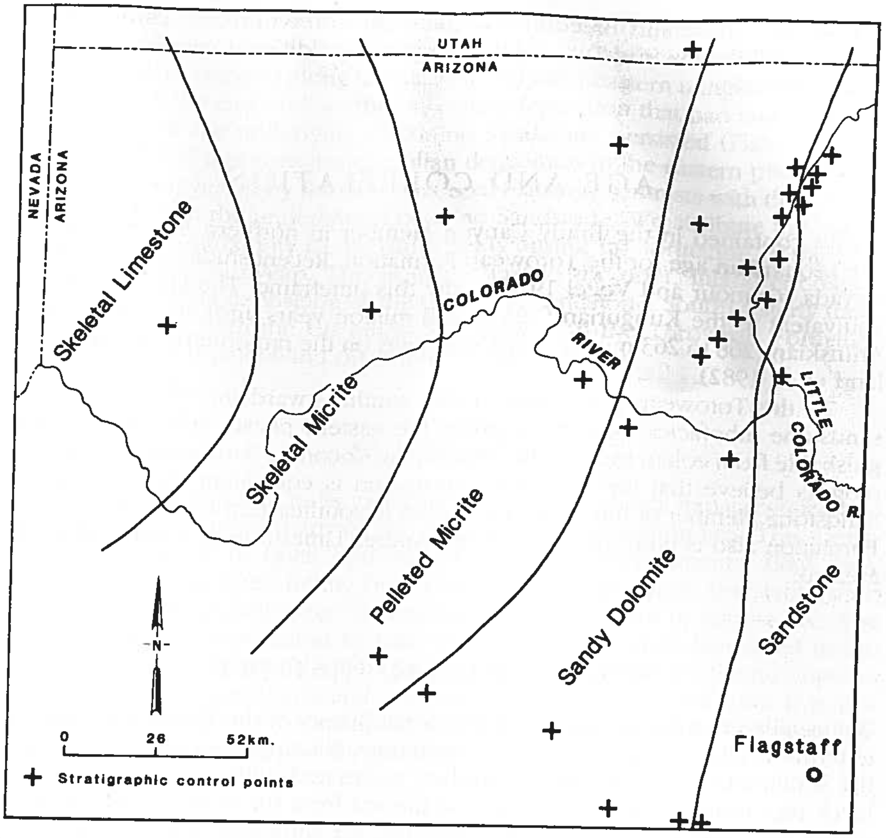

FIGURE 11.13. Lithofacies map of the Brady Canyon Member during time T-2 (see Fig. 11.12). (From Rawson and Turner-Peterson, 1974.)

PALEONTOLOGY

McKee (1938) summarized the paleontology of the Toroweap Formation in his original work on the Kaibab and Toroweap Formations. Except for the "Hurricane Cliffs tongue" of the Woods Ranch Member (which contains the marine bivalve *Schizodus*), the Brady Canyon Member is the only fossiliferous member of the Toroweap Formation. McKee recognized two major faunal facies in the Brady Canyon Member: an open-marine fauna to the west and a molluscan fauna to the east. The open-marine fauna includes brachiopods, bryozoans, crinoids, and horn corals. The molluscan fauna includes bivalves and gastropods, with a few scattered scaphopods and cephalopods. Kirkland (1962) compiled a faunal listing of subsequent finds in the Toroweap Formation. Belden (1954), Mullens (1967), Miller and Breed (1964), Beus and Breed (1968), Turner-Peterson (1974), and Rawson and Turner (1974) reported additional species in the Toroweap Formation.

AGE AND CORRELATION

Fossils contained in the Brady Canyon Member in northern Arizona suggest a late Leonardian age for the Toroweap Formation. Recent studies of bryozoans in Nevada (Gilmour and Vogel 1978) verify this timeframe. The late Leonardian is equivalent to the Kungurian (263 to 258 million years ago) and, possibly, late Artinskian (268 to 263 million years ago) ages on the radiometric timescale (Harland et al. 1982).

As the Toroweap Formation grades southeastward into the cross-bedded sandstone lithofacies that characterizes the eastern phase, it becomes indistinguishable from eolian rocks of the underlying Coconino Sandstone. Similarly, geologists believe that the Toroweap Formation is equivalent to the White Rim Sandstone Member of the Cutler Formation in southeastern Utah. The Toroweap Formation also is equivalent to the San Andres Limestone in northwestern New Mexico.

DEPOSITIONAL HISTORY

We usually interpret the overall depositional history of the Toroweap Formation in terms of relative sea-level changes with time. Subaqueous evaporate and tidal-flat sediments in the Seligman Member, associated with a relative rise in sea level, represented the first incursion of the sea from the west. Eolian sandstone within the member indicates times when the sea withdrew from the region. The development of a thick carbonate sequence in the Brady Canyon Member indicates an incursion of the sea as far east as the Marble Canyon area.

Near the end of the Brady Canyon deposition, a progradation of carbonate lithofacies occurred. This slowing down of the relative sea-level rise is reflected in the progradation of restricted-marine lithofacies at the top of the Brady Canyon Member to the west (R-3 in Fig. 11.12). The period of subaerial exposure indicated by abundant desiccation cracks at the top of the dolomitic mudstone marks a relative lowering of sea-level and subaerial exposure of the entire shelf.

With another incursion of the sea, probably in response to a relative rise in sea level, the shelf flooded again. Cyclic sedimentation of carbonate, evaporate, and sandstone in the Woods Ranch Member reflects conditions similar to those that persisted during the formation of the Seligman Member. Here, the evaporates and carbonates indicate periods of subaqueous deposition, whereas the eolian sandstones suggest times of subaerial exposure. Because no evidence for a barrier exists in the Woods Ranch Member of the Toroweap Formation, it is difficult to interpret the evaporate in terms of the traditional barred-basin model (Schreiber 1986). The evaporate lithofacies of the Woods Ranch Member extends as far as the Permian outcrops in Nevada—and without significant change. It thus appears that a shallowing of seawater across a broad shelf caused the restricted circulation that is required to generate a hypersaline brine for evaporate precipitation.

Away from the area of dominantly marine carbonate–evaporite sedimentation, tidal-flat, sabkha, and eolian depositional environments persisted throughout deposition of the Toroweap Formation. In the transition phase of the Toroweap, sediments were deposited chiefly in a tidal-flat environment. Siliciclastic sabkhas developed along the eastern and southeastern margins of the tidal flats. Farther to the east and southeast, eolian deposition that had begun during the formation of the underlying Coconino Sandstone persisted (Figs. 11.2 and 11.5). Evidence of moisture during eolian deposition in the eastern phase of the Toroweap, as suggested by the deformational features, contrasts with the scarcity of such features in the underlying Coconino Sandstone. We attribute this difference to the sea's proximity to the dune fields during the formation of the eastern phase of the Toroweap. This is in contrast to the drier, inland conditions that persisted during deposition of the Coconino Sandstone. Southwesterly transport directions in both the Coconino Sandstone and the Toroweap Formation are consistent with paleowind directions for the Permian.

SUMMARY

The Toroweap Formation, in its variety of lithofacies, reflects transgressions and regressions of an eastward-advancing and westward-retreating sea. The formation was deposited in open and restricted-marine environments, tidal flats, sabkhas, and eolian dune fields. During times of transgression, the stable shelf was flooded by shallow-marine waters that were conducive to marine life. The climate probably was semiarid to arid, and large dune fields developed in the inland regions. The shoreline commonly was in the vicinity of the Grand Canyon, which explains the striking lateral and vertical changes in lithofacies. It is this very variety of lithofacies in a relatively small area that makes the Toroweap Formation such a fascinating unit for geologists.