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SIGNIFICANCE OF PARABOLIC RECUMBENT FOLDS (PRFs) IN PERMIAN ROCKS, SEDONA, ARIZONA

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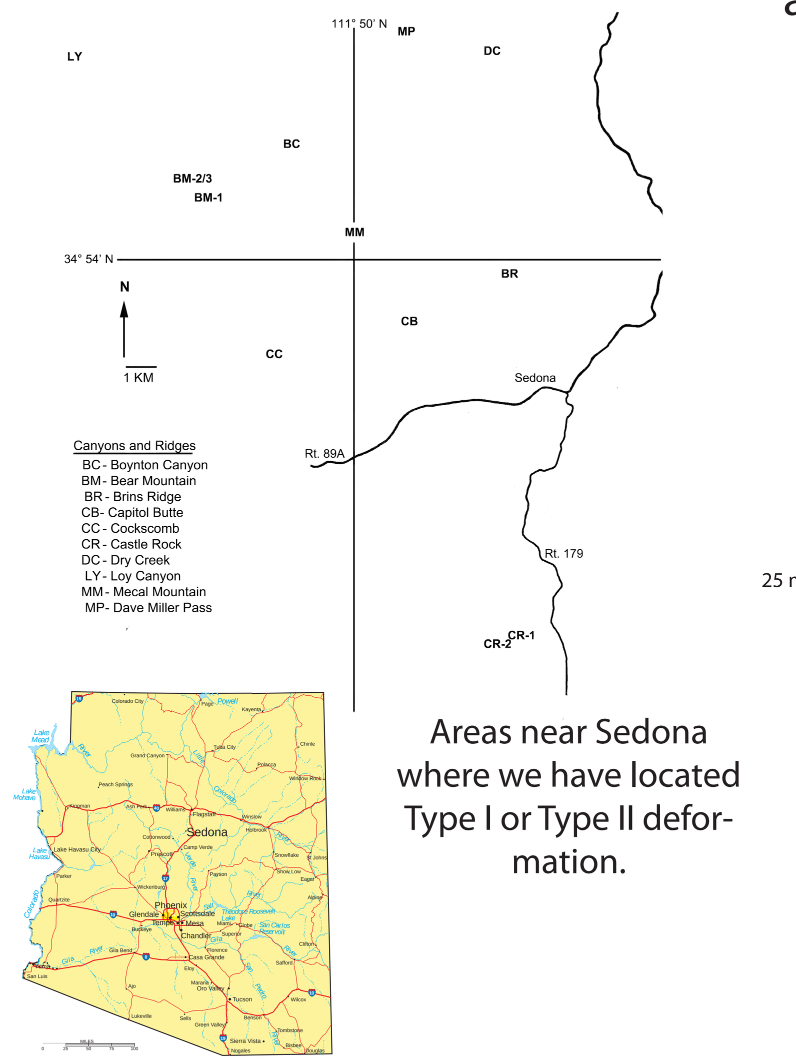
ABSTRACT

According to Allen and Banks (1972), subaqueously deposited cross-beds can penecontemporaneously deform via liquefaction to produce two major types of deformation: first are parabolic recumbent folds (PRFs) which appear like a series of parabolas lying on their sides; second are contorted cross-beds, where deformation is particularly present near the top of the set. In both types of deformation, bedding usually becomes faint or disappears near the top of the set. Although the exact mechanism of PRF formation is still debated, papers describing PRFs agree that strong water currents combined with liquefaction play major roles in overturning the top of a cross-bed set during deposition to form the fold types. PRFs are well documented in the literature from both fluvial and marine settings, modern and ancient. Published laboratory experiments have only produced the folds in subaqueous settings and have failed to produce them in dry or wet subaerial sands.

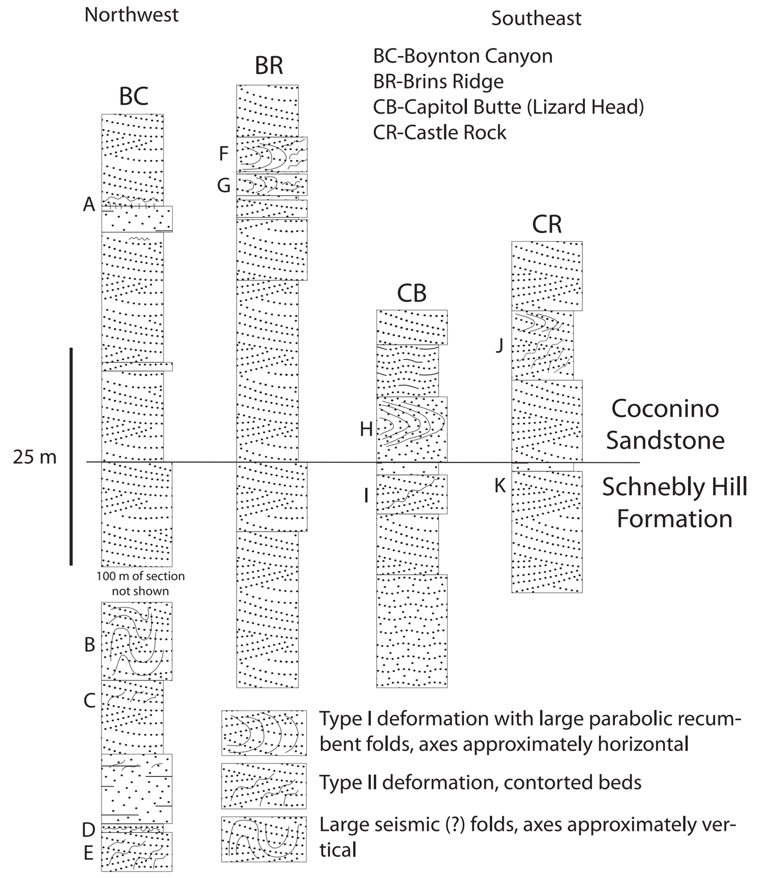
The cross-bedded portions of the Schnebly Hill, Coconino Sandstone and Toroweap Formations (Arizona, USA) are considered by most to be primarily eolian deposits. However, we have recently found multiple PRFs in all three of these formations. Deformed cross-bed sets occur over a wide area (>375 km^2) at many different locations and horizons, particularly in the Sedona area. Some PRFs in single cross-bed sets can be traced for 400 m along ridge tops. Field evidence shows the folding was penecontemporaneous. The folds in these rocks are quite specific and are identical in scale and form to PRFs produced experimentally in subaqueous sand and PRFs observed in many deposits of known subaqueous origin. There are specific features that distinguish PRFs from deformation structures in slumping eolian dunes. Some of the PRFs we have discovered are large-scale, ranging in size up to 5 m high, while slumping eolian dunes produce only small-scale folds and faults, usually at cm scales. There does not appear to be any evidence that the deformed beds are fluvial deposits within an eolian sand sea or that the deformation occurred by post-depositional groundwater movement or by seismic activity, as has been documented in other sandstones. These features are distinctly different. Where these folds occur, it suggests these formations were deposited by strong underwater currents.

Key Words: Schnebly Hill Formation, Coconino Sandstone, Toroweap Formation, soft-sediment deformation, parabolic recumbent folds

Folding in the Coconino Sandstone and Schnebly Hill Formation in the vicinity of Sedona, Arizona



Areas near Sedona where we have located Type I or Type II deformation.



What are PRFs?

Allen and Banks (1972), Doe and Dott (1980), and Hendry and Stauffer (1975) recognized three types of deformation in cross-bedded sandstones.

Type I folds (PRFs) appear as a long series of parabolas lying on their sides. The folds form as cross-bedded sand is liquefied and bent over by shear forces from the currents above, in the shape of a recumbent fold. The process occurs at the same time as deposition.

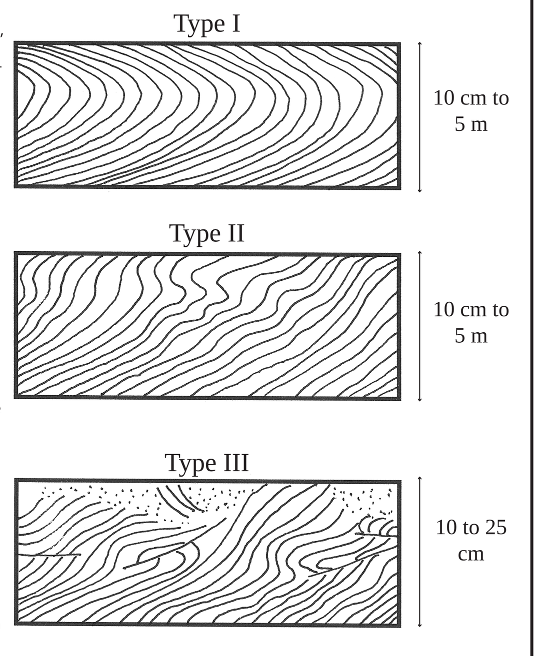
Type II deformation can transition into Type I folds. Deformation is often not as severe.

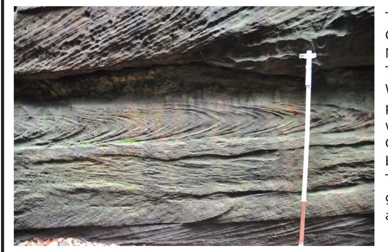
Type III deformation is typically found in eolian sands, or sand that is more cohesive. It is characterized by relatively small scale folds and faults.

Type I (or parabolic recumbent) are single recumbent folds, typically each following a smooth parabolic curve, the axial plane of which is close to horizontal. The "mouth" of the fold opens down-current. The hinge may occur at any level within the deformed unit, but typically occurs near the middle or upper part of the bed. The stratification in the lower part of the bed is well defined, but stratification in the upper part of the bed becomes faint or blurred and sometimes impossible to detect. In less well-developed examples, the upper strata are more steeply inclined, with no overturning of strata. The top of the fold is truncated as in an angular unconformity or sometimes becomes doubly recumbent. Based on published laboratory experiments, literature review and field observations, these types of folds most commonly occur in beds from 10 cm to about 2 m in thickness, with some even thicker. They have been produced experimentally but only in subaqueous settings. All previously known field examples occur in subaqueous cross-bedded sandstones (see table in Wells et al., 1993).

Type II (or contorted) are numerous folds that differ in the size, shape and attitudes of the axial planes. The largest and most complex folding (some of which may be disharmonic) occurs near the top of the cross-bed set. Near the bottom of the cross bed set, less folding and deformation occurs. As in Type I folds, stratification in the upper part of the cross-bed set may be blurred or absent. Faulting is absent. Type I and Type II folds can occur together in the same cross-bed set showing a genetic relationship between the two types of folding. The deformation can be mild or rather complex. Beds occur in thicknesses from 10 cm to 2 m.

Type III (or brecciated and faulted) includes deformation structures that contain a mixture of overturned folds, thrust faults, "crinkly" bedding and structureless sand. This type of deformation is relatively small scale (10-25 cm) compared to the other two types, and is only known to form in eolian settings from slumping of relatively cohesive (wet but not saturated) sand. McKee and Bigarella (1979) and McKee et al. (1971) illustrate many types of these deformation structures based on experimental work and field studies of modern dunes.





Type I PRFs from the Sharon Conglomerate, Cuyahoga Valley National Park, northeast Ohio. These folds were described by Wells et al. (1993) and are pictured for comparison with what we found. The Sharon Conglomerate is interpreted to be a large braided stream system. The picture on the left shows a group of folds which extend for about 20 m along the outcrop.

Experiments and Observations

Rettger (1935) found that significant folding does not occur in dry sand or wet sand, only in water saturated sand. McKee et al. (1962a, 1962b) found similar results in their experiments. In their experiments and observations of deformation in modern eolian sands, McKee et al. (1971) found that nine types of deformation structures typically occur in dry sand (rotated plates and blocks, stair-step folds and normal faults, stretched laminae, warps (gentle folds), drag folds and flames, high-angle asymmetrical folds, overturned folds and overthrusts, break-apart laminae and breccias, fade-out laminae). All of these structures are small scale (<25 cm, often less than 10 cm in size). Faulting and suturing of laminae is common in dry and wet sand, but does not typically occur in water-saturated sands. McKee and Bigarella (1979) illustrate some recumbent folds and thrust features from modern eolian dunes. These features are mostly laminae-scale deformations riddled with small faults and are not comparable in shape or scale to what we are describing from the Sedona area. PRFs have been produced in the laboratory, but only in water-saturated conditions; dry sand and wet sand give completely different results (McKee et al., 1962a). The folds in the Sedona area remain consistent in shape and size over great lengths (sometimes hundreds of meters) of the outcrop within single beds which have unconformably truncated tops. Transitions from cross-beds to folded beds can be found in the Sedona area and are similar to those recognized in subaqueous deposits like the Sharon Conglomerate of northeastern Ohio (Wells et al., 1993).

How do PRFs form?

Allen and Banks (1972) developed a model showing how shear forces from a strong current could recumbently deform strata if the bed was liquefied by seismic activity. As the sand is liquefied, the current contorts the bed in the down-dip direction. Experiments by Owen (1996, p. 290) "conclusively demonstrated that simple recumbent-folded cross-bedding is generated by tangential shear acting on a liquefied bed, and that sufficient shear can be provided by an aqueous current." Owen generated liquefaction by performing his experiments on a shaker table.

It is clear that liquefaction needs to occur for folding, but is seismic activity always responsible or are there some other triggers? Some PRFs have formed in areas that did not experience seismic activity. Hendry and Stauffer (1975), who studied folds in Saskatchewan, Canada, argued that PRFs can be made by strong sediment-laden currents, without seismic activity. This also appears to be the case in modern folds formed in the Brahmaputra River sands (Coleman, 1969). These types of folds are so abundant in cross-bedded sands that it is unlikely that strong syndepositional earth tremors caused all the folding, although earthquake activity could still be invoked for some folds. Thus, the formation of most of the folds by strong sediment-laden currents seems to be a reasonable explanation at this time (Wells et al., 1993). McKee et al. (1962a) produced recumbent folds in the laboratory with strong sediment-laden currents. Formation of recumbent folds by shearing of a tangential current is supported by thin-section study as well (Yagishita and Morris, 1979), but perhaps two other mechanisms of liquefaction of the basal sediment layer are possible.

Røe and Hermansen (2006) have suggested that recumbent folding can take place during changes in flow regime. They argued that cross-strata formed in the dune/plane-bed transition were deformed as the flow regime momentarily changed to plane-bed stage causing liquefaction at the dune front. The current then becomes sediment-laden (due to the liquefied sand), causing shear forces to deform the beds below. We do not know if this is the precise mechanism for the deformation of the cross-beds in the Sedona area, but we think it must be seriously considered. Flat-beds are extremely rare in the Coconino, with more occurring in the Sedona area than anywhere else we have observed (Whitmore et al., 2011). The close association of the Coconino flat-beds with the deformation structures we have found may indicate that currents are fluctuating back and forth between flow regimes. Everywhere we have found flat-beds in the Sedona area, deformed Coconino can be found in the vicinity.

Another possible mechanism suggested for liquefaction of bottom sediments is cyclic loading by sudden changes in the depth of the water column by waves (Molina et al., 1998; Owen and Moretti, 2011) and even tides (Greb and Archer, 2007). Either one of these mechanisms could potentially cause liquefaction and parabolic recumbent folding during deposition of cross-bedding in a subaqueous setting. Wells et al. (1993) suggested that one mechanism for deformed beds in the fluvial Sharon Conglomerate might be a sudden increase in water depth during a flash flood. It seems mechanisms like this might also be considered for deformation in the cross-beds of other rivers and deltas including the Brahmaputra River (Coleman, 1969), the Mississippi River delta (Coleman and Gagliano, 1965), Coos Bay Delta (Dott, 1966) and the Colorado River (McKee, 1938). PRFs have been observed in shallow marine sandstones of India (Mazumder and Altermann, 2007) showing that these features can occur in settings other than fluvial ones.

Brins Ridge (BR)

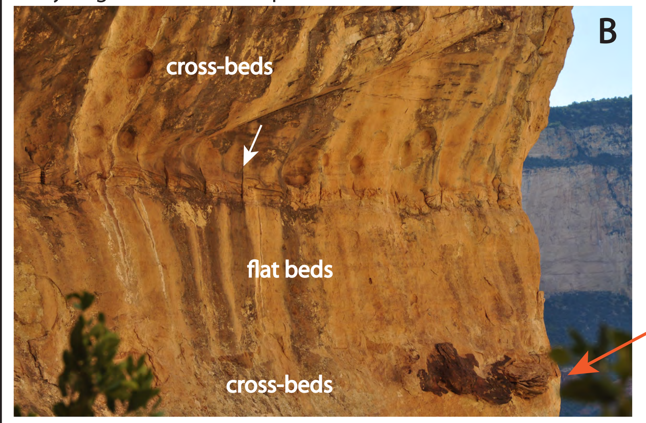
Along Brins Ridge, two sets of PRFs can be traced along the ridge top for at least 400 m (shown by arrows in Photo A). The folds transition back and forth between cross-beds and Type I & II folds. Photo A shows how the beds are associated with a flat-bedded horizon in the Coconino. Photo C shows some detail of photo A where the cross-beds transition into PRFs.

Photo B is a weathered fold from the horizon of lower folds shown in Photo A.

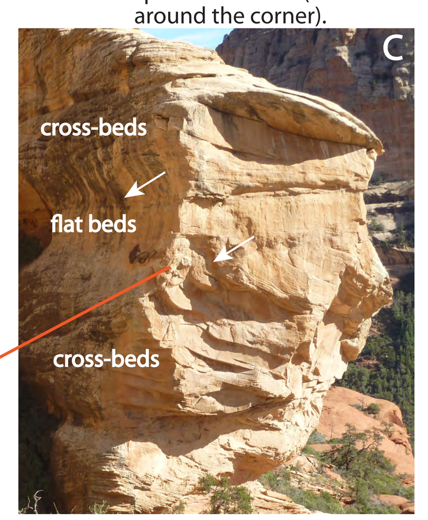
Boynton Canyon (BC)

The transition between cross-bedding and Type II folding in the Schnebly Hill Formation.

Type II deformation occurs just above and below this 3 m thick flat bedded unit. The top of the flat bedded unit has short joints (see arrow) that we do not know how to interpret. They might be water escape features.



Top arrow shows the short vertical joints of Photo B. The bottom arrow points to some Type II deformation about 2 m tall. Red arrow shows the location with respect to Photo B (it is around the corner).



Capitol Butte (CB)

PRFs at "Lizard Head", Coconino Sandstone. Photo A shows the largest PRF that we have found. It is associated with the PRFs in photo B. Photos A & B are both looking at the south face of Lizard Head. Photo C is on the opposite side of the ridge (north face). Arrows in photo C show the long and consistent nature of the fold (for at least 50 m).

Castle Rock (CR)

Type II fold in the Coconino Sandstone.

Type I fold in the Coconino Sandstone.

Coconino National Forest

Probable Type I fold in the Toroweap along with some additional soft sediment deformation. Rawson and Turner-Peterson (1980) report large recumbent folds that we have been unable to locate.

Type II deformation in the Coconino Sandstone along the Pine Creek Trail, near Pine, AZ.

Wupatki National Monument

A large PRF near the top of the Coconino in an exposure in Wupatki National Monument (northeast of Flagstaff).

The contact between the Coconino and Toroweap in Wupatki.

Significance of these findings

Parabolic recumbent folds have been produced experimentally in subaqueous sand and observed in many known subaqueous cross-bedded sandstones. Experiments have failed to produce them in dry and wet sand, probably because it is too cohesive. There are several theories regarding the formation of PRFs; all require subaqueous liquefaction and penecontemporaneous deformation by strong shearing currents that form the cross-beds. The presence of this specific type of deformation feature requires subaqueous conditions and has depositional implications for the cross-bedded portions of the Schnebly Hill Formation, the Coconino Sandstone and the Toroweap Formation. When PRFs are present they suggest a subaqueous origin, not an eolian origin for these formations.

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