Synsedimentary deformation in the Jurassic of southeastern Utah—A case of impact shaking?

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ABSTRACT

In southeastern Utah, the Middle Jurassic Carmel Formation and Slickrock Member of the Entrada Sandstone locally show convolute bedding and syndepositional folds. Newly recognized liquefaction features indicate that this deformation occurred rapidly. None of the five explanations found in the literature fully accounts for these features. The large scale of liquefaction and soft-sediment deformation is distinctive and implies strong disturbances that are difficult to explain by traditional structural or stratigraphic interpretations. Upheaval Dome, within the area of the deformation, displays in detail the structures expected of a complex, central-peak impact crater representing energy release at least equivalent to that of a magnitude 8 earthquake. Upheaval Dome is not well dated, but may be the same age as the deformation. We suggest that the Carmel–Slickrock Entrada deformation may be an example of folding and liquefaction due to impact shaking; if so, it would be one of a very few known cases. Although this kind of deformation should not be common, other examples should be recognizable in outcrop and from subsurface information.

INTRODUCTION

Almost every geologist who enters Arches National Park in southeast Utah (Fig. 1) must be struck by the unusual deformation in the Carmel Formation and the lower part of the Entrada Sandstone. The Carmel Formation is a widespread unit in southern Utah; in and around Arches it has been mapped as the Dewey Bridge Member of the overlying Entrada Sandstone, followed upward by the Slickrock and Moab Members of the Entrada (Doelling, 1985, 1988). In this paper we refer to the two units displaying the deformation as the Carmel and the Slickrock Entrada (Fig. 2).

In some portions of Arches National Park and nearby areas the Carmel and the Slickrock Entrada are contorted into trains of folds. This "wrinkled rock" interval (Fig. 3) is underlain by undeformed, cross-bedded Navajo Sandstone and in some places by a thin, planar-bedded unit probably representing the Page Sandstone Member of the Carmel (Peterson and Turner-Peterson, 1989; Havholm et al., 1993). The deformed interval is overlain by the undeformed upper part of the Entrada, above the middle of the Slickrock Member.

The Middle Jurassic Carmel Formation is a complex package of shallow marine, estuarine, sabkha, and eolian deposits (Blakey et al., 1983, 1988, 1996). In Arches, near its eastern limit, the Carmel is an easily eroded interval of red beds. The Entrada (Kocurek, 1981; Kocurek and Dott, 1983) shows facies variations on a regional scale, but in Arches, it is a resistant, cliff-forming sandstone, largely eolian in origin, with alternating white cross-bedded and pink planar-bedded layers. The contorted bedding was first noted during early studies by the U.S. Geological Survey (Gilluly and Reeside, 1927, p. 74, plates 18C, 19A; Baker, 1933, 1946; Dane, 1935; McKnight, 1940).

DEFORMATIONAL STRUCTURES IN AND AROUND ARCHES NATIONAL PARK

Intraformational folds occur locally in the Carmel–Slickrock Entrada interval at Arches and are particularly well displayed in the Windows Section. The folds terminate abruptly downward at or near the base of the Carmel. In most places they die out gradually upward within the Slickrock Entrada; in cliffs at the park entrance, they end at a local angular unconformity, apparently within the Slickrock Entrada. The folded beds thicken and thin irregularly, indicating lateral flowage. Some synclines are box shaped and have flat bottoms.

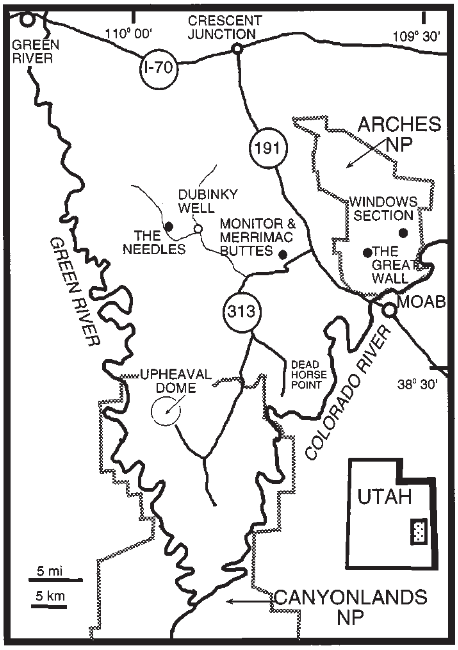

Figure 1. Location map of southeastern Utah study areas. Jurassic Carmel (= Dewey Bridge) outcrops are vertical faces tens of meters high that do not show well at this map scale, but they occur throughout Arches National Park (NP) and westward to Dubinky Well road and Needles area east of Green River.

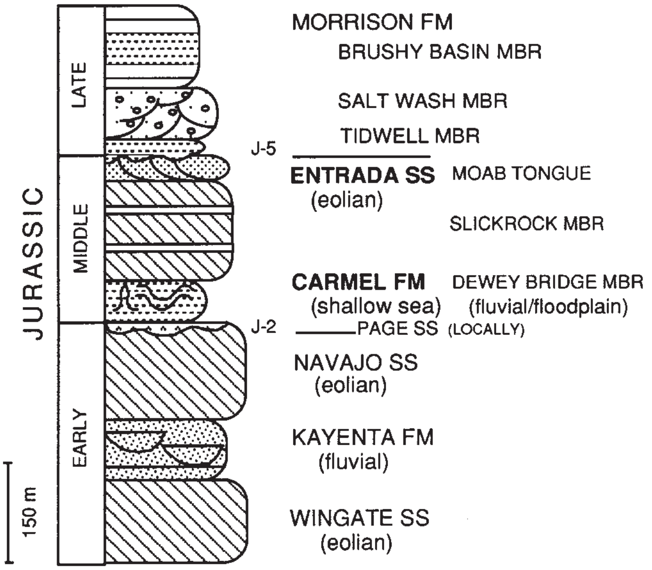

Figure 2. Jurassic stratigraphic units of study area. J-2 and J-5 indicate regional unconformities of Pipiringos and O'Sullivan (1978). Modified after Hintze (1988). FM—formation, MBR—member, SS—sandstone.

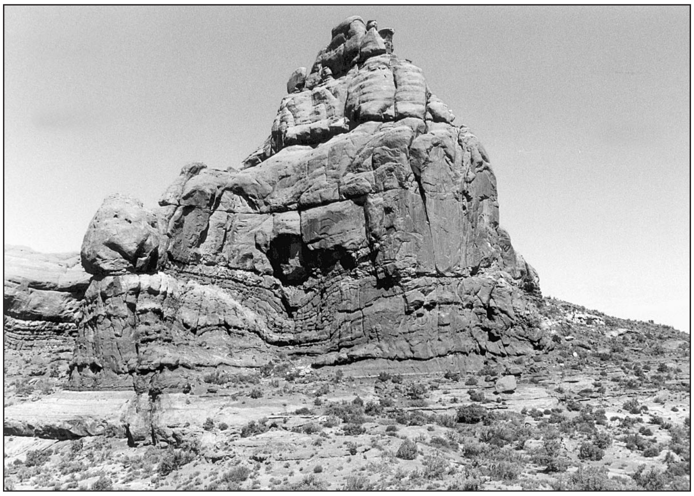

Figure 3. Ham Rock, in Arches National Park. Undeformed Navajo Sandstone (foreground) and white, planar-bedded Page Member of Carmel Formation are overlain by contorted Carmel Formation (= Dewey Bridge Member of Entrada Sandstone). Deformation gradually dies out upward, midway through Slickrock Member of the Entrada, near top of Ham Rock.

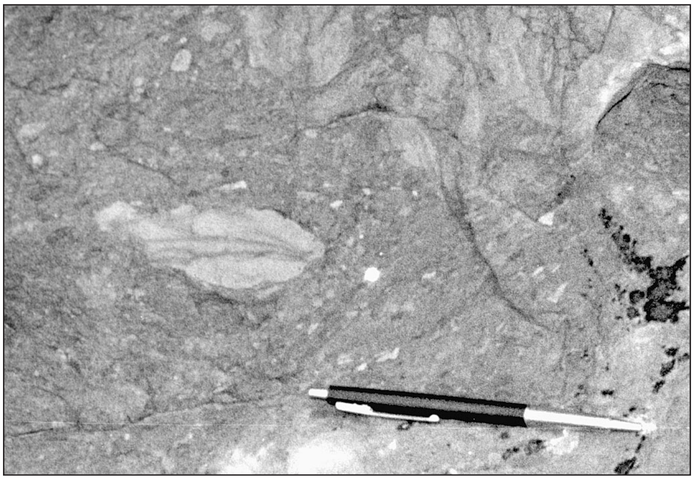

Figure 4. Complete disruption of Carmel bedding has produced a breccia.

We have seen no systematic orientation to the fold axes, and in one well-exposed case, a prominent synclinal axis bends abruptly. There is no indication of systematic vergence in the folds.

On a 10–100 m horizontal scale, the Carmel–Slickrock Entrada deformation varies in intensity. In order of increasing intensity of deformation, we recognize (1) undeformed beds, (2) undulating beds, (3) well-developed folds, (4) discontinuous, disrupted folds, and (5) disorganized bodies that appear to have sunk as density-loading features or risen as sand injections.

In some places, including North Window, the beds involved in folding were brecciated (Fig. 4) or even liquefied. Just west of the Windows Section we have seen a 10-cm-wide lateral transition between cross-laminated Slickrock Entrada and the same unit without laminae. This feature suggests that the laminae were destroyed and the sand homogenized through liquefaction.

Intrusive plugs or pipes of sandstone with dimensions from 1 cm to more than 10 m are common (Fig. 5) and can extend vertically up to several tens of meters. In one case, drag of abruptly terminated beds provides clear evidence for upward intrusion of a 10-m-scale mass of fluidized sediment (Fig. 6). Although we have yet to find a direct connection between sand intrusions and trains of folds, the upward removal of sand in some places may account for the prominence of flat-bottomed synclines in other places.

Deformation of the Carmel–Slickrock Entrada interval occurs in patchy areas with kilometer-scale dimensions. In Arches National Park, very slightly deformed Carmel and undeformed, cliff-forming Slickrock Entrada are exposed in the Great Wall but change laterally over just a few tens of meters to a strongly deformed condition that persists for at least 3 km to the north.

Doelling (1988) indicated that deformation within the Carmel (his Dewey Bridge Member) is most pronounced in eastern exposures (around Arches National Park), and that the unit thickens regionally to the west. In exposures of the Carmel due west of Arches (between Arches and the Green River, covering the Monitor and Merrimac Buttes area, the Dubinky Well area, and the Needles area; Fig. 1), deformation does appear to be less intense than that shown within Arches. These western exposures commonly show conformable basal and upper contacts of the Carmel. The greatest deformation occurs in the upper half of the Carmel, where fluvial and flood-plain deposits contain undulating and internally homogenized beds and intrusive sand pipes.

PROPOSED EXPLANATIONS

There is little discussion and no agreement in the literature as to what mechanism was responsible for the Carmel–Slickrock Entrada deformation. We have found five published hypotheses, listed here with pros and cons, followed by our suggestion of a sixth possible explanation.

1. Johnson (1969, 1970) invoked compressional buckling of sandstone multilayers. He idealized the Carmel as an alternation of soft and stiff beds, as the basis for mathematical analysis, without including detailed field observations. Pro: The fold geometry fits the buckled-multilayer model, in which thin-bedded rocks (Carmel) should buckle at shorter wavelengths than thick-bedded rocks (Navajo Sandstone and Slickrock Entrada). Con: The folds apparently lack the linear axes expected in tectonic compression. Sand injections, flow breccias, and localized changes in bed thickness show that the sand was in a fluid condition and deformed rapidly, rather than through a slow process like buckling.

2. Baars (1972, p. 175–176) attributed the deformation to sliding of soft sediments down a paleoslope. Pro: This mechanism fits the intraformational, syndepositional character of the folding. Con: It implies a consistent direction of transport and should have produced frontal compression, extension at the rear, and shearing at the base (Alvarez et al., 1985); we have not seen these features.

3. Kocurek and Dott (1983, p. 109) suggested dissolution of Carmel evaporites to explain the deformation. Pro: Evaporite dissolution could explain the predominance of synclines, some with flat bottoms, and the lack of consistent fold orientation. The Arches area has unquestionably been deformed by movement of the Pennsylvanian Paradox Salt at depth. Con: As Johnson (1969) noted, Arches is well east of the edge of significant evaporite thicknesses in the Carmel. No evaporite beds or veins are evident in the Carmel at Arches. Furthermore, dissolution of evaporites is a slow process, unsuited for explaining the sand injections.

4. Peterson and Turner-Peterson (1989, p. 31–32) attributed the deformation to loading of soft mud of the Carmel Formation (their Dewey Bridge Member) by overlying sand of the Slickrock Entrada. Pro: This could explain the predominance of synclines and the patchy occurrence of the deformation. Con: It is hard to postulate, in this environment, a way of loading the sediment rapidly enough to produce the evidently rapid emplacement of sand injections.

5. Rogers (1985) attributed the deformation to liquefaction caused by earthquake shaking. Pro:

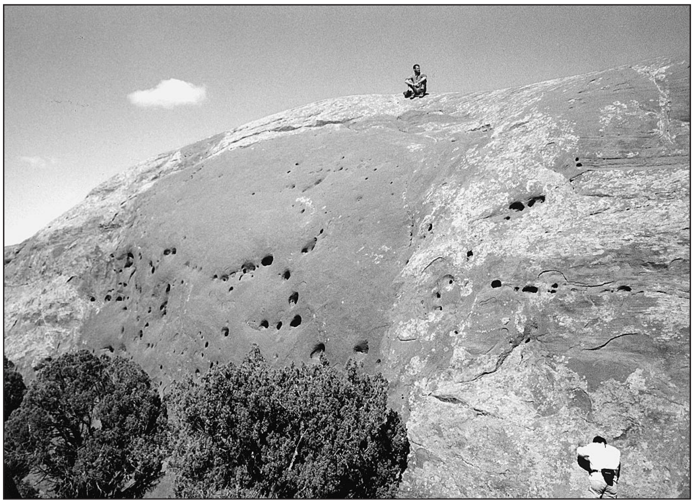

Figure 5. An apparent plug of red-brown sandstone (Carmel?), which has had its bedding destroyed and homogenized, is surrounded by cross-bedded lower Slickrock Entrada.

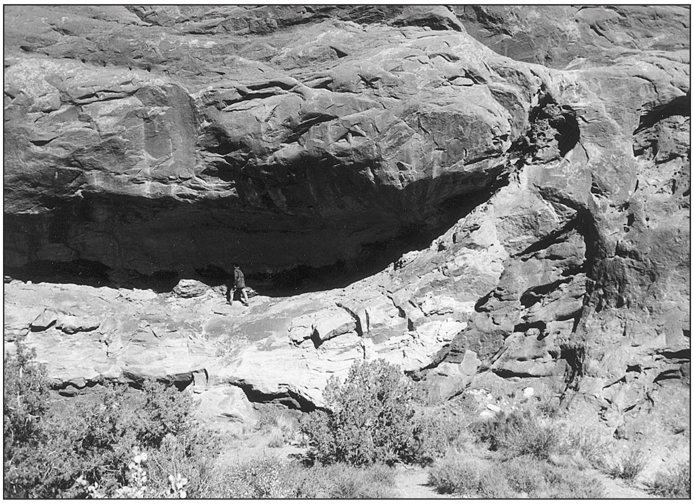

Figure 6. Massive bedding near contact between Carmel and Slickrock Entrada has been dragged upward by intrusion of sandstone body at right.

Seismogenic liquefaction (Committee on Earthquake Engineering, 1985; Obermeier, 1996) could explain the injection of sandstone pipes and the localized occurrence of deformation. Con: If the shaking were seismogenic, multiple events would be expected. We have seen no evidence for more than one event in the Carmel–Slickrock Entrada we have studied, but soft-sediment deformation is seen at several older horizons in thicker Carmel sequences in southwest Utah (Jones and Blakey, 1993).

6. The contorted Carmel–Slickrock Entrada in Arches is located ~40 km from Upheaval Dome in Canyonlands National Park. Strong new evidence, discussed below, indicates that Upheaval Dome is an impact structure. We suggest that the deformation could have resulted from shaking of unlithified soft sediment due to the impact at Upheaval Dome. Pro: Upheaval Dome lies within the area of deformed Carmel and Slickrock Entrada. It is southwest of the outcrops described in this paper, but in reconnaissance with R. T. Buffler we have noted similar deformation on the other side of Upheaval Dome, just west of the Green River and near Hanksville. Impact liquefaction would account for the observed fluidization structures and sandstone pipes (comparable to sand blows generated by earthquakes), and for the patchy occurrence of the deformation. Con: The impact at Upheaval is not well dated and cannot yet be tied directly to the Carmel–Slickrock Entrada deformation.

UPHEAVAL DOME

At Upheaval Dome a circular rim syncline, 4 km in diameter, preserving Lower Jurassic Navajo Sandstone (Huntoon et al., 1982), surrounds a 2-km-diameter bowl-shaped erosional basin, within which the Triassic Chinle and Moenkopi Formations rise in a central structural dome. Detailed mapping (Shoemaker and Herkenhoff, 1984; Schultz-Ela et al., 1994; Kriens et al., 1997b) has documented a pattern of concave-upward faults that accommodated motion toward the center of the structure, generating a central dome containing radially oriented folds and thrusts.

The presence of the Pennsylvanian Paradox Salt beneath Upheaval Dome led some geologists, beginning with Harrison (1927), to interpret the structure as a salt dome. Others, beginning with Boon and Albritton (1936), favored an origin as an impact crater. The salt-dome interpretation is now in doubt, because the structure displays in detail the features expected in a complex impact crater (i.e., a crater with a central peak) (Shoemaker and Herkenhoff, 1984; Kriens et al., 1997b): (1) 10–30 cm pieces of vesicular quartz-rich rock interpreted as devitrified impact ejecta, (2) shatter surfaces, (3) complex folding and top-toward-the-center thrusting in the central uplift, (4) top-toward-the-center normal faults farther out in the structure, and (5) abundant clastic dikes. In addition, Huntoon and Shoemaker (1995) invoked impact at Upheaval Dome to account for hydraulic fracturing ~15 km northeast of the dome, and seismic data show "no evidence of any salt diapir within 500 m below the dome's central depression" (Louie et al., 1995).

Shoemaker and Herkenhoff (1984) inferred erosion of 1–2 km of overburden since the impact occurred, which, if correct, would imply a crater age of Late Cretaceous or early Tertiary. The discovery of probable melt-rock ejecta lying on the eroded Navajo surface in the rim syncline (Kriens et al., 1997a) makes this interpretation untenable, for it would require that the ejecta be let down vertically, without being destroyed or carried away, during erosion of 1–2 km of rock. Kriens et al. (1997b) thus favored a fairly recent time of impact, "possibly as late as a few million years ago."

In a new interpretation, we suggest that the crater-forming impact may have occurred during deposition of the Entrada, and that shaking due to the Upheaval Dome impact may have caused the deformation of the Carmel and Slickrock Entrada. A Jurassic date for the impact is possible, considering the weak age constraints (it must postdate the Navajo), although it is not supported by any other evidence. Such a date is compatible with the discovery of probable ejecta on the land surface, because the stratigraphic thicknesses involved (Hintze, 1988, column 83) would allow the ejecta to be let down from an original depositional horizon within the Slickrock Entrada to the present surface during erosional removal of only 100–200 m of stratigraphy. The tough, cobble-sized ejecta bombs could survive during the weathering and removal of the Entrada and Carmel sand and silt. One of us (Alvarez) discussed the possibility of a Jurassic impact age with Eugene Shoemaker shortly before his death, and Shoemaker saw no reason to exclude this possibility, but we stress that this suggested crater age is a conjecture only.

Upheaval Dome is 1–3 times the diameter of the young, well-studied, 1 km Meteor Crater in Arizona, for which estimates of impact energy range from 0.7 to 25 × 10^{16} J (Melosh, 1989, p. 114). For comparison, the 1906 San Francisco earthquake (estimated Richter magnitude 8.25) released ~10^{17} J of strain energy (Bolt, 1978, p. 193, 214). Despite uncertainties in energy estimates and differences in energy partitioning in impacts and earthquakes, even modest impact craters represent energy release comparable to that of very large earthquakes.

We conclude that Upheaval Dome resulted from an impact of sufficient energy to have caused the Carmel–Slickrock Entrada deformation through impact shaking, and that an impact of this age is compatible with the weak constraints on the age of the crater.

IMPLICATIONS

The physics of impact on a consolidated target are reasonably well understood (Melosh, 1989), but little is known about what happens during impact on or near wet, unconsolidated sediments. About 10% of the Earth's surface lies within a couple of hundred meters of sea level, and roughly this percentage of impacts should generate shaking in sediments susceptible to liquefaction. One reported example is a field of sandstone plugs in close proximity to the Oasis impact crater in Libya, which "appear to be the result of upward movement of fluidized sand" (Underwood, 1976). A related case is the Devonian Alamo Breccia in Nevada (Warme and Sandberg, 1996; Warme and Kuehner, 1998), which represents impact disruption of a carbonate platform.

Although we cannot yet consider an impact-shaking origin for the Carmel–Slickrock Entrada deformation to be proven, there is sufficient evidence to take this hypothesis seriously. Other cases should exist, and it will be worth searching for them and reconsidering other examples of mysterious deformations in this light.

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